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Distributional cost effectiveness analysis of West Yorkshire low emission zone policies

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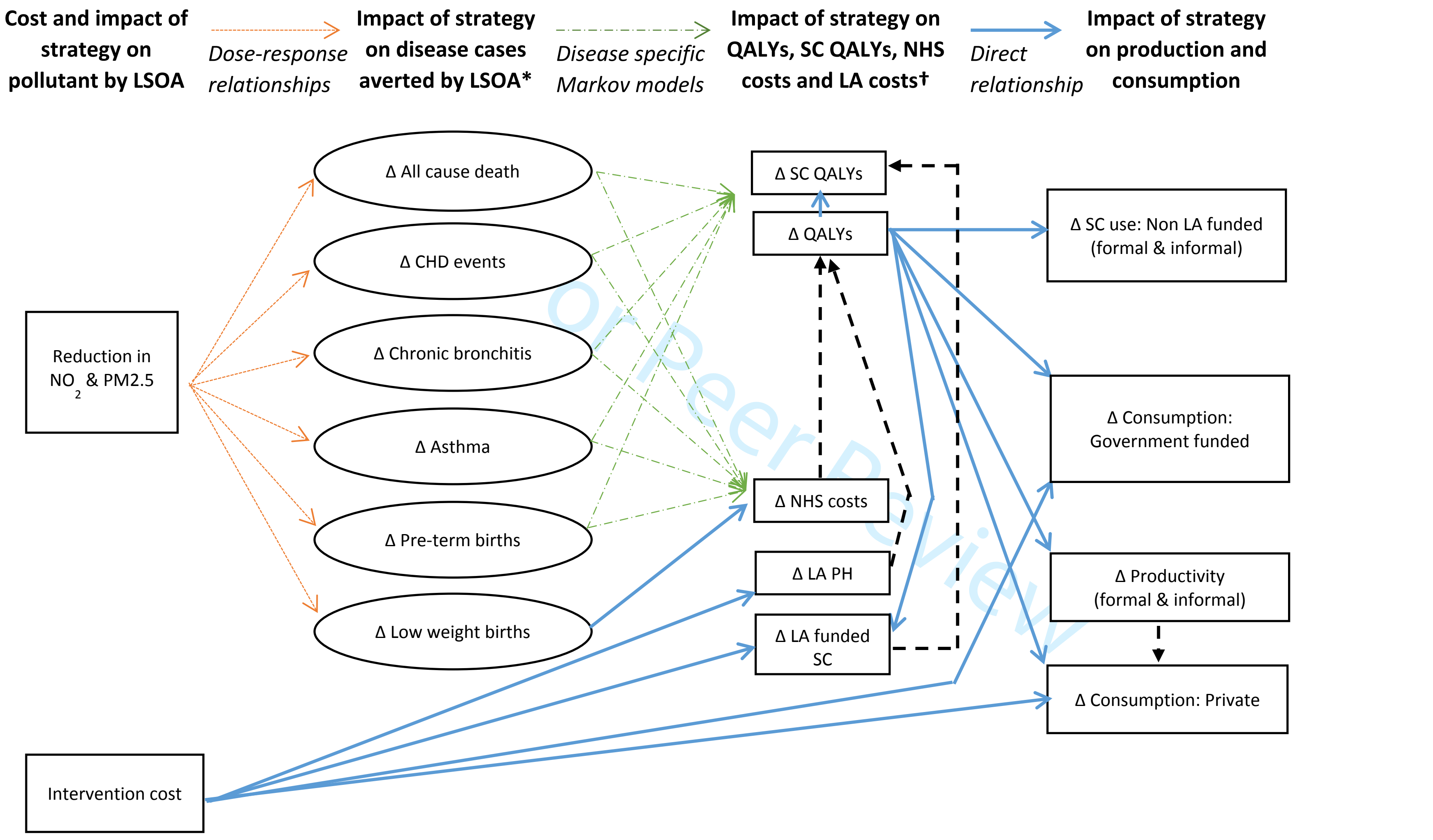

*For each LSOA population, assuming baseline event rate from MSOA and capturing full impact of lower exposure (no time lag); asthma restricted to those aged<19 during year of policy implementation

†Quality of life, mortality and NHS costs dependent on Index of Multiple Deprivation (IMD); SC QALYs measured for proportion of population receiving care

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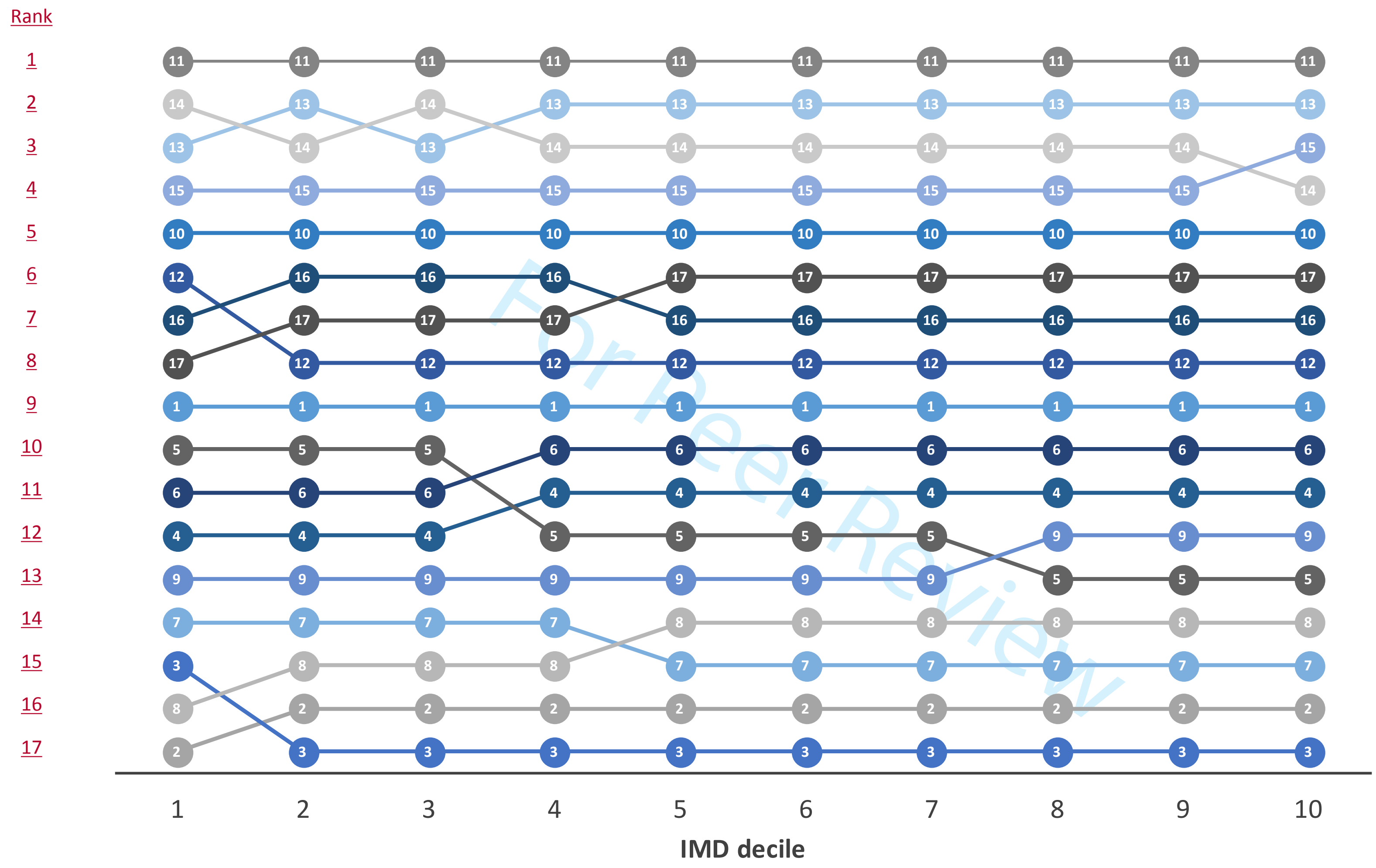

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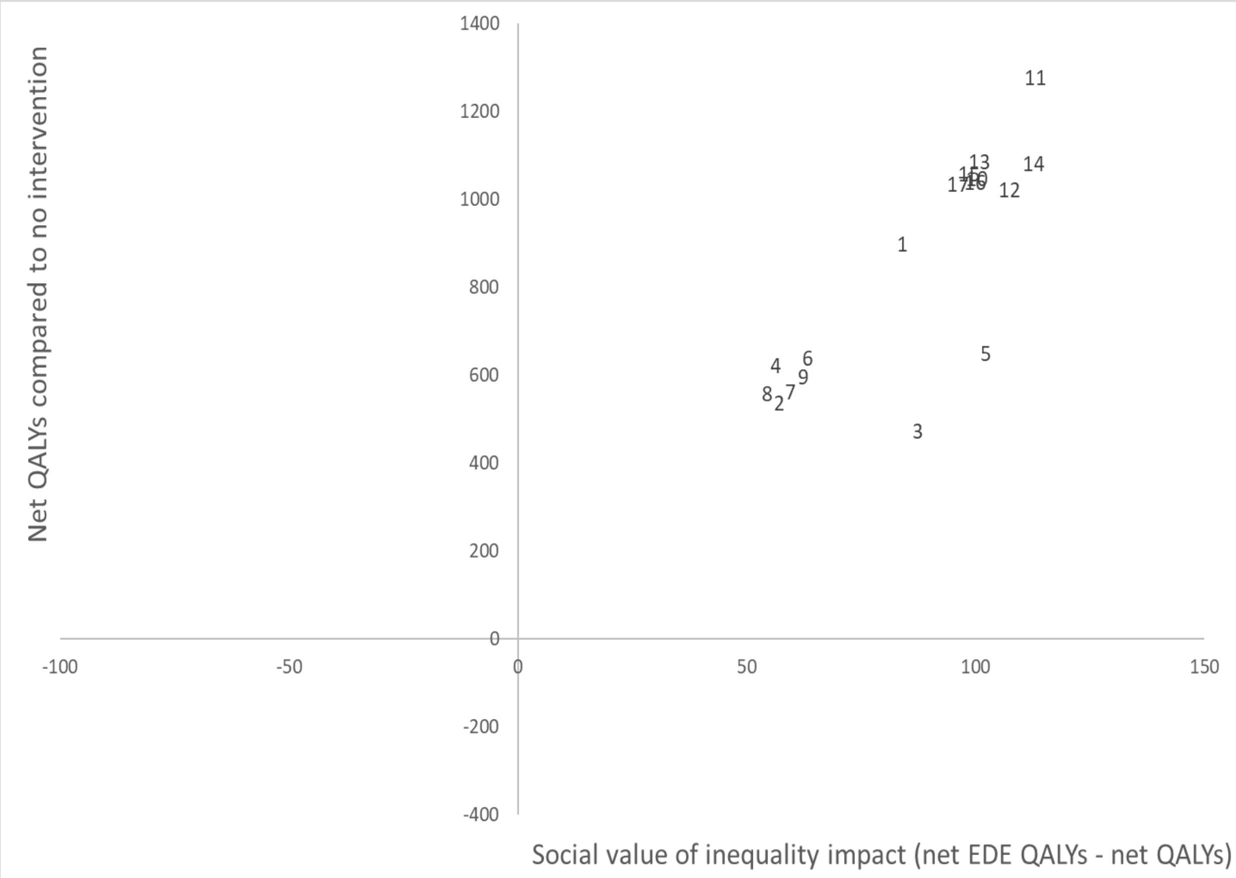
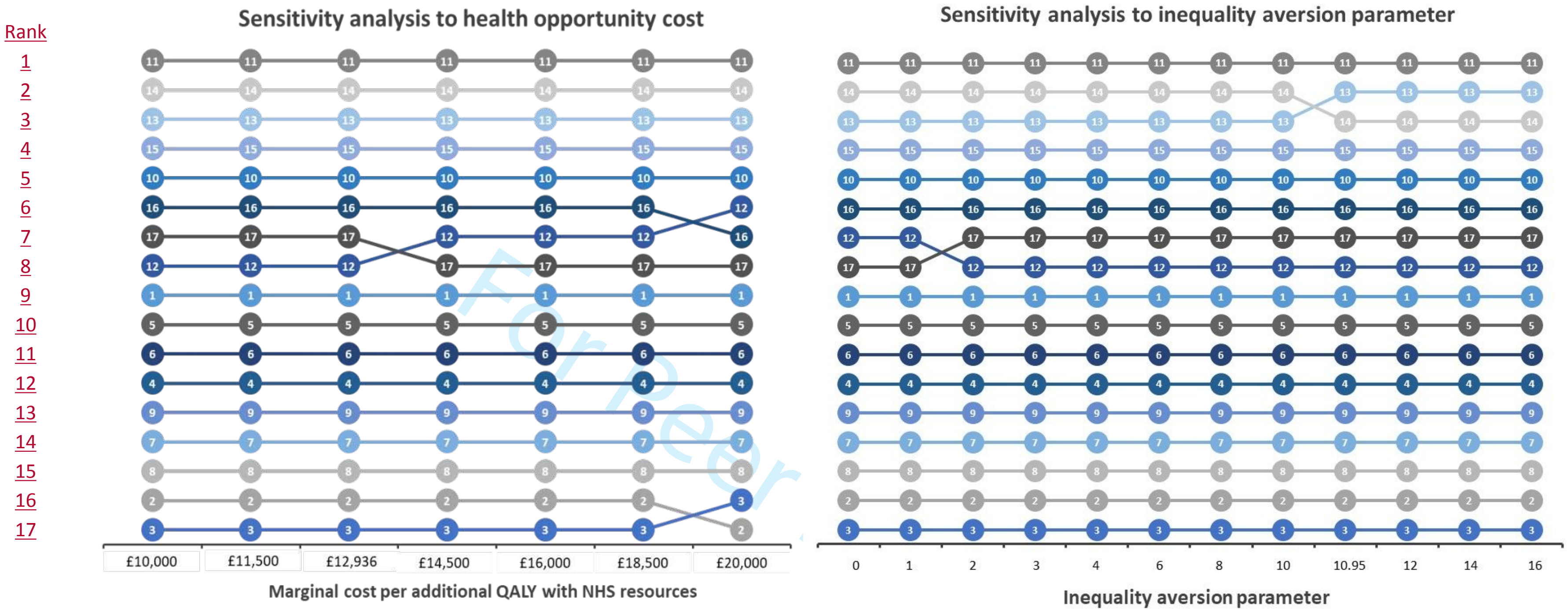


EDE = equally distributed equivalent; QALYS = quality adjusted life years



QALY = quality adjusted life year

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Abstract: Alternative strategies can reduce road vehicle emissions, with differential effects on exposure across population groups. We compare alternative strategies in West Yorkshire using a framework for economic evaluation that considers multiple perspectives and that takes account of the distribution of health outcomes.

Exposure to pollutants by area is converted, via dose response relationships, into disease averted. Health benefits and NHS costs from diseases are estimated conditional on population demographics and index of multiple deprivation. The net health benefits from alternative strategies are expressed as distributions of quality-adjusted life expectancy (QALE), which are compared using dominance criteria and societal aversion to health inequality. Net production is estimated from intervention costs and the effects of health improvement on production and consumption. Social care outcomes are estimated from health improvement among care recipients and changes in care expenditure.

A switch to less polluting private vehicles is dominant in terms of the distribution of QALE and social care outcomes, but not consumption. Inclusion of health inequality aversion alters the rank order compared to prioritisation on health maximisation. The results were sensitive to the magnitude of health opportunity costs, the level of inequality aversion and the proportion of intervention cost that generates health opportunity cost.

Key words: Economic evaluation, health inequalities, decision analysis, air pollution

1. Introduction

Disadvantaged groups are often subject to greater exposure to air pollution, and are more susceptible to ill health effects from exposure.(Deguen et al., 2010) A range of different interventions can improve air quality, which may have differential effects on the level of exposure across population groups. The range of policies differ in their cost implications, and who bears the opportunity costs will have important implications for conclusions about overall benefit and net health inequality impact. Few studies have evaluated the health inequality impacts of air quality strategies, and inconsistent results indicate that beneficial effects cannot be presumed.(Wang et al., 2016)

The West Yorkshire Zone was identified as having the fourth most significant NO_2 concentration issues in the UK, with exposure concentrated in deprived inner-city areas. Exposure to atmospheric particles smaller than 2.5μm ($PM_{2.5}$) was estimated to be responsible for 1 in 20 deaths in the area, and a health impact assessment showed that efforts to reduce this mortality would produce the largest benefits in the most deprived areas.(Cooper et al., 2015) A previous study developed a model to show how cost effectiveness analysis from a health service perspective can be used to evaluate interventions to reduce transport emissions.(Lomas et al., 2016) However, the cost-effectiveness of low emission zones was deemed uncertain in recent National Institute for Health and Care Excellence (NICE) guidance.(National Institute for Health and Care Excellence, 2017) The cost benefit economic analysis undertaken for NICE used a "damage cost" method that applied a consumption value to convert direct health benefits (damages avoided) into monetary values to produce a benefit-cost ratio, but did not consider the health opportunity cost associated with healthcare resources.(Watkiss et al., 2006) These previous economic evaluations considered a single strategy to reduce road vehicle emissions, and did not estimate the size or value of health inequality impacts.

This study updates and extends the previous cost effectiveness analysis to compare multiple strategies for reducing road vehicle emissions in terms of the impact on the distribution of health and to consider the implications of who bears the opportunity cost of the alternative schemes. In consideration of the distribution of the opportunity cost, we also present impacts on non-health outcomes related to consumption and local authority expenditure, but we do not attempt to combine these with health outcomes. Instead, we show how evaluation of health inequality impact and other considerations may influence the prioritisation of different strategies.

2. Methods

We apply a framework for economic evaluation to inform multiple decision makers, and consider the viewpoint of three stakeholders: the healthcare sector, local authorities, and individual citizens.(Walker et al., 2019) We assume that the healthcare sector is concerned with improvement of health outcomes in terms of increasing population health and reducing health inequalities. The UK Health and Social Care Act 2012 requires that resource allocation decisions in healthcare are made with due regard to the reduction of inequality in health outcomes associated with socioeconomic factors. We therefore assume that, at the societal level, health inequality associated with socioeconomic factors is regarded as unfair, and that reduction of this inequality would improve societal welfare.

Local authorities in the UK are responsible for public services relating to social care, transport planning and highways, public health, housing, planning, leisure and environment, and for monitoring air quality in their areas. When evaluating changes in air quality we assume that their concern is for improving health and social care outcomes and the local economy. We consider impacts on individuals in terms of health related quality of life, social care related quality of life, life expectancy, and production and consumption of good and services.

We therefore have multiple stakeholders with an interest in health outcomes, and between whom we assume that the health opportunity cost associated with expenditure on strategies to reduce vehicle emissions could differ. Where interventions use public sector funds and draw from specific budgets, the opportunity cost is in terms of a restricted set of other activities that could have been provided with the same set of resources. That is, the set of relevant alternatives and opportunities is constrained by institutional context. Monetary willingness to pay and willingness to accept values elicited from individuals denote the opportunity cost of alternative uses of private income, and are inappropriate for valuing opportunity cost in relation to specific budgets.(Drummond et al., 2015) For example, the opportunity cost of NHS resources is not determined by free choice of alternative investments. Investment in building a car factory or upgrading train stock would not be options to fund from NHS resources. Instead, the opportunity cost is in terms of alternative investments that fall within the remit of the NHS. Correspondingly, when a particular budget is already fully spent, any investment that imposes costs on that budget necessitates disinvestment from other activities supported by that budget. The relevant stakeholders also have multiple objectives (health, social care, production and consumption), and the valuations they attach to these different objectives are not explicit.

2.1 Direct health impacts of each strategy

Strategies to reduce road vehicle emissions include efforts to upgrade vehicle stock to produce lower emissions through better technology and by moving away from diesel as a fuel source. The health impact assessment to inform the feasibility of a West Yorkshire Low Emission Zone provided lower layer super output area (LSOA) level information on the expected change in exposure to pollutants (NO_2, $PM_{2.5}$, PM_{10}) for 17 alternative transport emission reduction strategies (shown in Table 1). LSOAs are geographic areas with an average population size of 1,500 individuals used by the Office for National Statistics in the UK for many of its statistical outputs. They can be mapped to local healthcare funders (clinical commissioning groups), local authority districts and area based measures of socioeconomic deprivation.

Local area health profile data produced by Public Health England provided the baseline levels of pollution-linked disease in each middle layer super output area (MSOA) in the period 2010-2014, which comprise coronary heart disease, chronic bronchitis, asthma, low weight births, preterm births and all-cause mortality. Each LSOA within an MSOA was assigned the same baseline rate of events. Dose response functions from meta-analyses and studies recommended by COEMAP link change in pollution exposure in each area to change in incidence of pollution-linked disease.(Cesaroni et al., 2014; Colbourn et al., 2007; Department of Health Medical Directorate Respiratory Team, 2010; Favarato et al., 2014; Hoek et al., 2013; Mangham et al., 2009; Pedersen et al., 2013; Sapkota et al., 2012; Schikowski et al., 2014; World Health Organisation, 2013) These determine the absolute number of cases averted for each LSOA, according to the size and age structure of the population in each local authority reported in the 2011 ONS census[1].

We combine this with a set of Markov models for each pollution linked disease that estimate the health benefits and NHS cost from each case averted based on external data on mortality, health-related quality of life and NHS costs conditional on the index of multiple deprivation (IMD).(Asaria et al., 2016; Kind et al., 1999; Love-Koh et al., 2015; Office for National Statistics, 2017) The index of multiple deprivation is a measure that ranks the deprivation level of an area based on the proportion of people in that area who experience deprivation in the domains of income, employment, health, education, access to services, living environment, housing and crime.(Noble et al., 2006) For the purposes of our analysis, it allows us to describe inequality in outcomes by area level deprivation (a bivariate measure of health inequality by IMD), and, through the link between IMD and healthy life expectancy, to describe inequality in outcomes by differences in baseline level of health (a univariate measure of health inequality). Table A1 in the appendix summarises the data sources and assumptions used across the combined models, which estimate the health benefits of cases averted in terms of quality adjusted life years (QALYs) and NHS costs over a lifetime horizon. Figure 1 provides a summary of the modelled relationships.

We incorporate information on the baseline distribution of healthy life expectancy in the UK so that we can express outcomes in terms of both the change in health and the absolute level of health.(Love-Koh et al., 2015) We characterise different susceptibility to air pollution in terms of area baseline incidence of pollution related disease, which confers a differential absolute harm from a given level of pollutant by area. We also characterise different capacity to benefit in terms of competing impacts on mortality and quality of life by socioeconomic status. In the absence of evidence that socioeconomic status modifies the relative effect of air pollution, we use the same dose response relationship for given pollutants across population groups.(Laurent et al., 2007)

2.2 Direct non-health impacts

Previous work to estimate the wider societal benefits of health interventions has estimated the link from health status to productivity and consumption, including both formal and informal (unpaid) activities, and including social care.(Roberts, 2015) This allows us to link improvements in health related quality of life to increased production and decreased consumption by age and sex, and show how additional quality adjusted survival has different impacts on production net of consumption according to the beneficiary's age and sex. Health related quality of life varies by IMD within our model, and this introduces additional socioeconomic variation in the wider societal benefits over and above that caused by the differential health impacts by IMD and the differential wider societal benefits by age and sex. For non-health outcomes, we consider only the total change attributed to each strategy and do not estimate the distribution or the absolute level.

A UK population study estimated an 'exchange rate' between health related quality of life (as measured by EQ-5D) and social care related quality of life (ASCOT). It provides an equation to predict ASCOT from EQ-5D, and vice versa (EQ-5D-3L = −0.04883 + 0.978042*ASCOT). (Stevens et al., 2018) We use this within the Markov models to convert health-related quality of life into social care

[1] http://www.ons.gov.uk/ons/rel/census/2011-census/key-statistics-for-local-authorities-in-englandand-wales/rft-table-ks102ew.xls

related quality of life to estimate the impact of strategies on a preference based measure of social care needs and wants (social care QALY).

We assume that additional consumption represents a direct benefit to individuals separate to the benefit derived from health outcomes (i.e. consumption value is not included in the QALY). We assume that changes in individuals' consumption not matched by changes in production impose a direct cost (for excess consumption) or direct benefit (for excess production) to other individuals, in terms of impact on their consumption. For any changes in expenditure on formal social care activities, we assume that 45% is local authority funded, with the remaining paid privately or supported by other means (e.g. the third sector).

2.3 Opportunity costs

Although the intervention costs are not borne by the NHS, the strategies alter the amount of NHS expenditure on air pollution related health events. The health opportunity cost of NHS expenditure is based on an estimate of the marginal productivity of the health sector and how a marginal QALY produced by the NHS is distributed by IMD.(Claxton et al., 2015; Love-Koh et al., in submission) This showed that the most deprived tenth of the population derive almost twice the benefit of NHS expenditure compared to the least deprived tenth. In the absence of evidence on the marginal productivity of local authority public health funds, the health opportunity cost of local authority public health spend is assumed to be in line with that of NHS expenditure. These opportunity costs allow us to convert changes in total NHS resource use and local authority public health expenditure for each strategy into health opportunity costs, which are summed with the direct health benefits from reduced exposure to air pollution. As for the direct non-health benefits, the health opportunity costs are converted into corresponding changes in individuals' production and consumption. We estimate the change in social care outcomes that accompany these health opportunity costs by again applying exchange rate between EQ-5D and ASCOT.

The cost of the intervention falls to the local authority for strategies that improve the bus stock, and to individuals for strategies that seek to encourage the switch to lower emission private and freight vehicles. The majority of local authority spend in the UK is on social care (59% across adult and children social care) with smaller proportions spent on public health (8%), and highways and transport (5%).(National Audit Office, 2017) Thus, money spent on transport policies by a local authority may displace public health activities, but will also generate opportunity costs on other outcomes additional to health. We assume that 8% of local authority funds spent on improving the bus stock would otherwise have been spent on public health interventions and hence generate health opportunity costs. We assume that 59% of the money would otherwise have been spent on formal care and produce opportunity costs in terms of social care related quality of life. The remaining 33% is assumed to produce opportunity costs in other local authority produced goods and services measured in terms of expenditure. This assumption that opportunity costs fall in proportion to average expenditure in each category may be unrealistic, and we test alternative assumptions in sensitivity analysis.

The social care opportunity cost of formal care expenditure is based on an estimate of the marginal productivity of the social care sector.(Forder et al., 2014) The distribution of this opportunity cost is unavailable, and so we use the value of one social care QALY per £50,000 to calculate the total opportunity cost.

We describe the opportunity costs borne by individuals in terms of consumption. These include the financial cost of strategies to improve private vehicles and the financial cost of strategies to improve freight vehicles. Regulations to improve private vehicles and freight vehicles force individuals to increase their consumption in that domain. We do not estimate health opportunity costs from consumption impacts.

2.4 Health inequality impacts

The results are expressed in terms of the distribution of quality-adjusted life expectancy (QALE) under each strategy and without any intervention for the population covered by the West Yorkshire Low Emission Zone. The sum of quality-adjusted life expectancy across all 1.27 million residents of Leeds and Bradford (ONS census 2011) provides the total population health benefit under each strategy. Inequality can be assessed with respect to individuals ranked by baseline health (a univariate distribution of health) or ranked by IMD decile (a bivariate distribution of health by area level disadvantage). Leeds and Bradford is relatively disadvantaged compared to the UK, with 340,953 (27%) residents living in areas ranked within the most deprived IMD decile, and only 478,158 (38%) residing in areas ranked above the median IMD. The alternative distributions of quality adjusted life expectancy are first compared using stochastic dominance to determine if the strategy that offers the greatest population health benefit can also be judged to offer the greatest reduction in health inequality. First order stochastic dominance occurs if a strategy provides the greatest health for any individual (i.e. across the whole distribution).(Saposnik, 1981) For example, if we line up the population in order (from lowest IMD to highest) and plot each members QALE for two alternative strategies, we would find first order stochastic dominance if the curves for each strategy never crossed. Second order stochastic dominance can be found if, as quality adjusted life expectancy is summed across individuals ordered from worst off to the best off, the sum is always greater than that of any other strategy.(Shorrocks, 1983) That is, if we line up the population in order and then plot the accumulated QALE as you move from lowest to highest IMD, we would find second order stochastic dominance if the curves for each strategy never crossed. Second order dominance can exist when first order does not, but only for a strategy that offers the greatest health for the lowest ranked individual.

Stochastic dominance produces only a partial ordering of strategies if any of the cumulative health distributions are observed to cross. When a strategy improves mean population health but may increase some concept of health inequality, we must be more specific about the nature of the inequality aversion to determine a ranking. By specifying the nature and the level of the inequality aversion, a normative value for inequality in a distribution of health can be determined. We summarise the value of each strategy using equally distributed equivalent QALE derived from an Atkinson index. The equally distributed equivalent increases with the total amount of health, and decreases as relative inequality in the distribution increases. The Atkinson index describes the percentage by which the overall value is reduced by relative inequality in a distribution.(Atkinson, 1970) The inequality aversion parameter (ε=10.95) required to estimate the value loss from inequality in the distribution of health is taken from a UK general population survey that estimated the amount of population health respondents would be willing to forgo to reduce health inequality between poor and rich individuals.(Robson et al., 2017) Comparing how an intervention alters equally distributed equivalent QALE to how it alters overall QALE (the unweighted health benefit) lets us describe the value of the health inequality impact in terms of health outcomes (QALYs). For example, if an intervention increases equally distributed equivalent QALE by more than it increases QALE, the difference is attributable to a reduction in health inequality.

We explore whether the rank order of the strategies differs in terms of total population health benefit versus equally distributed equivalent health benefit to determine whether concern for relative health inequality by IMD might alter the preferred strategy for introducing a low emission zone.

2.5 Sensitivity analysis

Probabilistic sensitivity analysis is used to determine the impact of parameter uncertainty on the results. The distributions assigned to model parameters are described in Table A1. The 3,000 Monte Carlo simulations drawn for the probabilistic analysis are used to calculate the error probability, which is the probability that a strategy other than the one selected using current evidence satisfies the given objective (for example maximising population health). The error probability should be interpreted in light of the number of strategies; for a random (uninformed) choice, the error probability is higher with 18 strategies (94%), than with two (50%). The cost of parameter uncertainty is the difference between the expected outcomes based on current evidence and the expected outcomes possible with perfect information, and this can be reported in terms of QALYs or equivalent health sector funding (based on the marginal productivity of the NHS). The cost of parameter uncertainty represents the maximum possible value of further efforts to generate evidence to inform the parameters for the current decision problem.

Local authorities may seek a grant from the Department of Transport to implement a low emission zone. In this case, the opportunity cost of the intervention cost is in terms of broader Government expenditure and not local authority public health or social care expenditure. Alternatively, we may assume that all local authority expenditure would otherwise have been spent on public health interventions, and generate health opportunity costs.

The opportunity cost applied in the analysis determines both the level of health benefit and the level of the health inequality impact. Uncertainty in the marginal productivity of health resources is incorporated in the probabilistic sensitivity analysis. However, we also conduct one way sensitivity analysis to illustrate how the results vary to alternative mean values for the health opportunity cost (between one QALY per £10,000 and one QALY per £20,000).

Where a strategy is found to have stochastic dominance over others, the rank order will not change for different values of inequality aversion. In the absence of stochastic dominance we conduct threshold sensitivity analysis on the value of the inequality aversion parameter (between 0 and 16).

3. Results

The model predicts health to be monotonically increasing with IMD for all strategies, such that ranking the population in terms of decile of IMD produces the same order as ranking those groups by QALE conditional on IMD. All strategies improved QALE compared to no intervention in all IMD deciles. Table A2 in the appendix shows the population QALE by IMD decile and the population size in each decile, the total population QALE and the equally distributed equivalent QALE, for each strategy. It can be seen from Figure 2 that strategy 11 (return petrol:diesel fuel split to Year 2000 levels within 7 years) has first order stochastic dominance over all other strategies. It produces the superior distribution of health by providing both most health overall and the most health within each IMD decile. Correspondingly, it is associated with the highest equally distributed equivalent QALE, and this would not alter regardless of the inequality aversion parameter applied. A dominant strategy in terms of providing the best result across all outcomes when impacts on overall health and health inequality are jointly considered is evident in Figure 3, the health equity impact plane; moving to strategy 11 from the origin (no intervention) or any other strategy entails moving up and to the right, increasing both population health and the societal welfare from reduction in health inequality.

3.1 Impact of health inequality on prioritisation

Comparing the remaining strategies in Table 2, the rank order changes with incorporation of health inequality concerns for strategies 13 and 14. Moving from strategy 13 to strategy 14 on the health equity impact plane entails moving down (less population health) and to the right (greater societal welfare from reduction in health inequality). If judged on total population health alone, strategy 13 (upgrade HGV stock to Euro VI standards by 2021) which provides an additional 1088 QALYs compared to no intervention, would be preferred to strategy 14 (all bus and HGV Euro VI by 2021), which provides a net gain of 1084 QALYs compared to no intervention. However, strategy 14 reduces health inequality by a greater degree than strategy 13, providing 1197 EDE QALYs compared to no intervention as opposed to the 1189 provided under strategy 13. As can be seen from Figure 2, strategy 14 provides greater health gain in IMD decile 1 (most deprived) and IMD decile 3 compared to strategy 13.

3.2 Alternative perspectives

Table 2 also indicates how the rank order of the strategies alters for different perspectives. Strategy 11 is ranked first in terms of net impact on social care quality adjusted life years, but only two strategies maintain the same rank as they would using a health perspective. Strategy 11 cannot be regarded as dominant if the perspective includes impacts on production and consumption because it no longer provides the greatest improvement in all outcomes. Strategy 6 increases net production by £10,779,566 more than strategy 11, but provides 638 fewer QALYs and 688 fewer equally distribution equivalent QALYs. If the consumption value of an additional year in full health is at least £16,895 (i.e. if it would be considered appropriate to trade at least £16,895 of consumption for one QALY), strategy 11 would be preferred over strategy 6.

3.3 Sensitivity analyses

Based on the results from the probabilistic sensitivity analysis, Strategy 11 is the most likely to provide the maximum health and the maximum equally distributed equivalent health, but for both the error probability is 75%. Of the remaining strategies, no intervention and strategies 2-9 have <1% probability of providing the maximum health or equally distributed equivalent health, while strategies 10 and 12-17 have between 8% and 13% chance of maximising health or equally distributed equivalent health. The cost of parameter uncertainty is similar whether the choice of strategy is aimed at maximising health (452 QALYs or £5,847,490 in health sector funding) or maximising equally distributed equivalent health (486 QALYs or £6,288,161 in health sector funding).

All strategies maintain stochastic dominance over no intervention when health opportunity costs are varied between £10,000 and £20,000. As seen in Figure 4, the ranking of strategies 2, 3, 12, 16 and 17 is sensitive to variation in the health opportunity cost. The ranking of strategies 12, 13, 14 and 17 is sensitive to variation in the inequality aversion parameter. Strategy 11 is the preferred strategy for all combinations of health opportunity cost and inequality aversion parameter.

The base case assumes that 8% of local authority expenditure would otherwise have been spent on public health interventions. Table 3 shows the results for alternative assumptions (0% and 100%). Strategy 11, which is not funded through local authority expenditure, maintains stochastic dominance over the alternatives, but health distributions for the remaining strategies that are funded by the local authority are affected. The greater the percentage of local authority funds that would otherwise have been spent on public health interventions, the lower are the net gains in population QALE. If 100% of the local authority funds required to implement strategies would otherwise have been invested in public health interventions, strategies 3 and 5, which impose the greatest cost burden on local authorities, are found to have a negative net health impact compared to no intervention. Increasing the percentage of local authority funds that generate health opportunity costs also increases the impact of health inequality concerns on the ranking. With 0% of local authority funds incurring health opportunity costs inclusion of health inequality affects the rank order of strategies 4 and 9, but at 100% the rank order affected for strategies 2, 7, 9, 12 and 14.

4. Discussion

This is the first economic evaluation of strategies to lower road vehicle emissions to take account of health inequality impacts and inform the prioritisation across multiple alternative strategies. Evidence on the impact of each strategy on pollutants at LSOA level allowed us to link changes in health to IMD. The availability of evidence to link pollutants to health events and to vary the health outcomes and opportunity costs according to IMD allowed us to translate change in pollutant levels to a change in the distribution of health. The impact of strategies to tackle air pollution goes beyond the health sector, but previous attempts at adopting a 'societal perspective' have failed to expose fully the consequences for each relevant stakeholder. Our approach represents an improvement by reflecting health and non health outcomes both in terms of direct impacts and opportunity costs.

In comparing the distribution of health generated by each strategy and by no intervention, we were able to rank the strategies to inform decisions about which would be preferred to implement a low emission zone given the focus on health. Stochastic dominance identified a preferred strategy considering impacts on the distribution of health without the need to specify the type and level of societal aversion to health inequalities. However, stochastic dominance did not provide a complete ranking of strategies, for which it was necessary to summarise and value health inequality impacts relative to changes in overall population health. We showed how the Atkinson index and equally distributed equivalent health provide a full ranking when stochastic dominance does not. However, the level of inequality aversion is uncertain, and can be difficult to measure without bias.(Cookson et al., 2018) This leads to uncertainty in conclusions about the ranking of strategies that increase population health but increase inequality relative to another, or that reduce inequality and produce less population health compared to another. We have shown how sensitivity analysis can elucidate this uncertainty.

While the main focus of this paper is on the distribution of health, this may not be the sole or primary concern for decision makers responsible for implementing a low emission zone. We considered wider societal benefits associated with changes in health in terms of production, consumption and social care outcomes. Estimating both local authority costs and direct benefits from formal social care provides information for decision makers interested in social care related quality of life. Local authorities are also responsible for public health, and so consider health outcomes alongside social care related quality of life, but the relative value local authorities place on these outcomes is unknown. In our case study, the optimal strategy does not alter regardless the relative values of health and social care outcomes, but a set rank order for all strategies would require an explicit trade-off. Consumption impacts are important to demonstrate the implications of shifting cost from the public sector to private individuals. Consideration of net production invites consideration of how much increased consumption is valued relative to improvements in health. In our analysis the threshold was a consumption value of at least £16,895 per QALY in order to prefer strategy 11 over strategy 6 on the basis of impacts on health and production, which is below the value of £60,000 per QALY suggested by the Department of Health.(Glover et al., 2010)

Even with a health focus, the conclusions about net population health benefit depend on whether resources used to fund the low emission zone would otherwise have been spent on health generating activities, and the size of the health opportunity cost associated with those funds. While there is currently evidence on the distribution of the health opportunity cost of NHS resources, we relied on the assumption that the health opportunity cost of local authority expenditure is the same as for the NHS. Given the role of local authorities in improving public health, improving knowledge of this opportunity cost is important.

The underlying model we use to demonstrate the evaluation of air pollution policies for multiple perspectives and different concerns about health inequality brings together a diverse evidence base to estimate multiple outcomes, but is relatively simple and static. Increasing the complexity of the model, for example to reflect the time lag between exposure and outcome or the behavioural impacts of policies, might produce more accurate results. Nevertheless, the framework we present here for analysing and presenting those results would still apply. There is also a lack of evidence to inform the distribution of the non-health outcomes and the weight society may place on reducing inequality. Publicly funded social care in the UK has a larger pro-poor bias compared to health care expenditure (3.9 ratio of benefits in kind received by bottom fifth of the income distribution relative to the top fifth, versus 1.8 ratio for health care).(Sefton, 2002) Potentially, the burden of opportunity costs from local authority formal care expenditure is borne more heavily by the most deprived compared to health care.

A societal perspective for economic evaluation is often advocated to capture effects across multiple domains. This is challenging to implement in the absence of an explicit social welfare function, and eliciting an agreed stated societal value of health relative to other outcomes is unlikely to be feasible.(Arrow, 1963; Walker et al., 2019) The simple summation of private costs with healthcare costs and local authority costs would be inappropriate given the potentially different opportunity costs of specific budgets. Even if it were possible, a single summary societal perspective result is unlikely to inform multiple heterogeneous stakeholders that may have different values for different outcomes.

Previously the cost effectiveness of low emission zones was considered uncertain by NICE. In our analysis the optimal approach to introducing a low emission zone is uncertain, but it is not uncertain that outcomes will improve compared to no intervention. For decision makers that value reduction of health inequality alongside increases population health, quantifying health inequality impacts as we have done here may strengthen the assessment of value for money.

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Table 1. List of strategies and estimated costs

Strategy name and number	Strategy details	Total cost (£million)	Location intervention cost burden
1. Fuel split by 2016	Return petrol:diesel fuel split to Year 2000 levels within 2 years	£103.1	Private vehicle owners
2. Euro II and Euro III bus retrofit by 2016	Retrofit Euro II and Euro III buses within 2 years	£3.4	Local authority
3. All buses Euro VI by 2016	Upgrade bus stock to meet Euro VI standards within 2 years	£34.7	Local authority
4. All HGV Euro VI by 2016	Upgrade HGV stock to meet Euro VI standards within 2 years	£54	General population
5. All bus and HGV Euro VI by 2016	Upgrade bus and HGV stock to meet Euro VI standards within 2 years	£88.7	Local authority and general population
6. All vans Euro VI by 2016	Upgrade all private vans to Euro VI with 2 years	£187	Private vehicle owners
7. Pre Euro IV bus to Euro VI by 2016	Upgrade pre Euro IV buses to meet Euro VI standards within 2 years	£3.9	Local authority
8. Pre Euro IV HGV to Euro VI by 2016	Upgrade pre Euro IV HGVs to meet Euro VI standards within 2 years	£2.4	General population
9. Pre Euro IV bus and HGV to Euro VI by 2016	Upgrade pre Euro IV buses and HGVs to meet Euro VI standards within 2 years	£6.3	Local authority and general population
10. Pre Euro V buses and HGVs to Euro VI by 2021	Upgrade pre Euro V buses and HGVs to meet Euro VI standards within 7 years	£4.2	Local authority and general population
11. Fuel split by 2021	Return petrol:diesel fuel split to Year 2000 levels within 7 years	£110.6	Private vehicle owners
12. All buses Euro VI by 2021	Upgrade bus stock to meet Euro VI standards within 7 years	£10.8	Local authority
13. All HGV Euro VI by 2021	Upgrade HGV stock to meet Euro VI standards within 7 years	£8.8	General population
14. All bus and HGV Euro VI by 2021	Upgrade bus and HGV stock to meet Euro VI standards within 7 years	£19.6	Local authority and general population
15. All vans Euro VI by 2021	Upgrade all private vans to Euro VI with 7 years	£61	Private vehicle owners
16. Pre Euro V buses to Euro VI by 2021	Upgrade pre Euro V bus stock to meet Euro VI standards within 7 years	£2.7	Local authority
17. Pre Euro V HGV to Euro VI by 2021	Upgrade pre Euro V HGV stock to meet Euro VI standards within 7 years	£1.5	General population

Table 2. Rank order of strategies according to different model outputs

	Health outcomes				Non health outcomes				
	Change in QALYs compared to no intervention		Change in EDE compared to no intervention		Social care			Production less consumption	
Strategy	**QALYs**	**Rank**	**EDE QALYs**	**Rank**	**LA expenditure**	**Social care QALYs†**	**Rank by social care QALYs**	**Net production‡**	**Rank**
1	900	9	984	9	-£102,159	11	5	£7,425,759	4
2	538	16	595	16	-£47,664	4	11	£969,681	17
3	474	17	561	17	-£67,536	-33	17	£1,028,952	16
4	624	12	680	12	-£61,650	8	9	£6,664,052	6
5	651	10	753	10	-£99,129	-31	16	£7,077,241	5
6	640	11	703	11	-£59,221	8	8	£19,961,308	1
7	563	14	622	14	-£53,069	3	13	£1,071,713	15
8	559	15	613	15	-£48,182	8	10	£1,259,043	14
9	597	13	659	13	-£58,361	4	12	£1,420,422	13
10	1049	5	1150	5	-£130,662	9	6	£2,826,334	9
11	1278	1	1391	1	-£170,300	14	1	£9,181,722	2
12	1023	8	1130	8	-£133,998	0	15	£2,656,160	11
13	1087	2	1188	3	-£135,017	13	2	£3,679,144	8
14	1084	3	1196	2	-£145,008	0	14	£3,761,783	7
15	1058	4	1157	4	-£129,039	12	3	£8,780,689	3
16	1040	6	1140	6	-£128,975	9	7	£2,644,130	12
17	1036	7	1132	7	-£125,632	12	4	£2,754,903	10

QALY = quality adjusted life year; EDE = equally distributed equivalent; LA expenditure = local authority expenditure on formal care

†Social care QALYs includes local authority formal care expenditure converted into social care QALYs using the opportunity cost of social care funds(Forder et al., 2014)

‡Excludes local authority expenditure on formal care and Government expenditure on health

Table 3. Sensitivity analysis on opportunity cost of local authority intervention funds

	Opportunity cost of LA funds all on Government expenditure (0% public health)				Opportunity cost of LA funds all on public health (100% public health)			
	Change in QALYs compared to no intervention		Change in EDE compared to no intervention		Change in QALYs compared to no intervention		Change in EDE compared to no intervention	
Strategy	**QALYs**	**Rank**	**EDE QALYs**	**Rank**	**QALYs**	**Rank**	**EDE QALYs**	**Rank**
1	900	9	984	9	900	5	984	5
2	559	16	614	16	296	13	378	14
3	688	11	754	11	-1994	17	-1654	17
4	624	13	680	14	624	9	680	9
5	866	10	946	10	-1817	16	-1462	16
6	640	12	703	12	640	8	703	8
7	587	15	644	15	285	14	373	15
8	559	17	613	17	559	10	613	10
9	621	14	681	13	319	11	410	13
10	1066	5	1165	5	857	6	977	6
11	1278	1	1391	1	1278	1	1391	1
12	1090	3	1190	3	255	15	441	12
13	1087	4	1188	4	1087	2	1188	2
14	1151	2	1256	2	316	12	507	11
15	1058	6	1157	6	1058	3	1157	3
16	1057	7	1155	7	848	7	968	7
17	1036	8	1132	8	1036	4	1132	4

LA = local authority; QALY = quality adjusted life year; EDE = equally distributed equivalent