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Measuring the equity effects of a carbon charge on car commuters: a case study of Manchester Airport

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Abstract

This papers attempts to quantify the equity effect of a hypothesized economic instrument, a carbon charge on car commuters, for reducing carbon dioxide emissions produced by commuters on airport surface access. Manchester Airport is taken as a case study using staff survey data from 2008 and 2010. Commuters' welfare change is analysed for measuring the equity effects of carbon charge by user group, which considers the changes of travel mode choice, the carbon dioxide emissions reduction, the revenue from a carbon charge and how it is distributed. First, the individual carbon footprint in terms of gram passenger kilometre, and the damage cost of carbon by commuters on airport surface access are estimated. Next, the impact of carbon charge on travel behaviour is investigated by the nested logit model. Finally, the net effect of carbon charges is assessed by travel mode user, gender, job type, and age group. The results show some impacts of the carbon charge on car users and carbon reduction, and the positive effects on lower income group and less carbon commuters. The quantified results provide the evidences for the mitigation policies to combine monetary incentives with disincentives for travel behaviour change, and demonstrate the different equity effects among commuter groups.

Keywords: airport commuters, the damage cost of carbon dioxide emissions, equity effects, nested logit model, consumer welfare

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1. Introduction

This study aims to assess and quantify the equity effects of a hypothesised economic instrument, a carbon charge on car commuters, as an abatement method to reduce the carbon dioxide (CO_2) emissions produced by commuters in airport surface access by using a case study of Manchester Airport.

Policy drivers encourage airports to reduce emissions not only directly from airports but also from surface access, including passengers and commuters (ACI, 2008; Department for Transport, 2004; Department for Transport, 2007). The emissions from surface transport used by passengers and airport employees are airports' second largest emission source, after aircraft emissions. For instance, they accounted for more than 38% of total emissions, after aircraft-related emissions (56%), at London Gatwick Airport in 2008 (BAA London Gatwick Airport, 2009). This demonstrates the importance of the management of surface access transport emissions at the airport. The airport has an important role in reducing emissions, although this is not straightforward (ACI, 2009). In particular, it is complicated for commuting employees. Since the airport companies themselves have not been seen to be addressing the problem, it is difficulty to persuade staff of third-party companies to change their own travel behaviour, (Budd et al., 2011; Humphreys and Ison, 2003).

The number of individuals travelling to the airport increases along with airport development. Among others, airport workers generally commute along the same routes every day. The influence of commuters' behavioural changes on environmental benefits can be large in the long term. Therefore, an effective cost–benefit analysis of airport commuters' surface access is required for the airport's master plan, together with the local community. The assessment should take account of externalities including climate change-related gases, such as CO_2 emissions.

A UK Government White Paper (Department for Transport, 2004) encourages the greater use of public transport for airport surface access, including that of passengers and commuters. Under Airport surface access strategies (ASASs; Department for Transport, 1999), which feed into Local Transport Plans, airport operators are responsible for implementing strategies to encourage individuals' use of public transport for airport surface access. These plans require long-term, large investment for implementation, since many stakeholders, such as local governments, train operators, local residences, are involved.

Humphrey et al., (2005) discussed policy instruments for dealing with employee surface access policies, including incentives for public transport users and disincentives to car users by means of car parking space restrictions and road pricing. The allocation-of-parking theme has a key role in employees' commuting policies not only for the airport, but also for all working environments (Russo et al., 2012). Indeed, Manchester Airport has taken several actions to improve public transport, such as large investment in rail and coach stations and cycling facilities and restricting parking allocation (Manchester Airport, 2007). However, no specific economic incentive or disincentive measures have yet been introduced, according to the interviews with Manchester Airport.

The private sector, including airports, is reluctant to internalise external costs (e.g. the cost of CO_2), particularly in the current economic downturn. However, internalising external costs improves economic efficiency while at the same time redistributing welfare between different groups (Maddison et al., 1997; Van Wee, 2011), such as high- and low-income groups. There exists the issue of equity among employees, and perhaps airports (e.g. large airports and small airports). Indeed, car ownership costs have increased in the past decade due to higher fuel prices, and could increase further if additional environmental taxes are imposed. While high-income groups can afford car travel for their commute, relatively low-income groups will be more inclined to change to public transport or cycling if car ownership costs continue to increase (Taylor et al., 2009).

The transport sector is the third largest source of greenhouse gas (GHG) emissions in the UK (Tight et al., 2005). Short-term behavioural change is crucial if the benefits of new technology are to be fully realised (Chapman, 2007). Disincentive policies such as fuel taxes, road pricing and car parking restrictions have been employed and have worked effectively in order to fill the difference between private and social costs and thus improve efficiency (Gallo, 2011; Santos et al., 2010). In addition, the positive impacts of revenue from congestion charges may result in an overall reduction of social exclusion (Raje, 2003).

In the case of the airport, entry pricing for taxis or drop-off charges can work to restrict entry and thus change travel mode behaviour. At the same time, monetary incentives to reduce the number of car users at work, such as parking charges or carbon charges, can be implemented. Indeed, economic instruments such as congestion charges and parking fees are often expressed as an efficient method to reduce the demand or to change the travellers' behaviour (Eliasson and Mattsson, 2006; Nakamura and Kockelman, 2002; Rotaris and Danielis, 2014). Another possibility is the introduction of car-sharing schemes to reduce emissions and congestion by providing commuters with incentives to share their car travel with others (see, for example, Department of Transport, 2004 for experiences at London Heathrow Airport). These various measures have differentiated effectiveness and equity effects.

An important difference between financial instruments and non-financial instruments is that in the first case, revenues are generated that can be distributed to address equity effects.

This study attempts to assess a hypothesised carbon abatement scheme, which is a carbon charge on car commuters working at airports. This is an entry charge for car commuters; however, it does not depend on the duration of parking. The rationale behind a carbon charge on car users is based on the 'polluter pays' concept, with a combination of incentives and disincentives for car users to discourage lone car use and encourage a travel mode shift to other modes, such as public transport. It also generates revenue to be able to offer monetary incentives to green commuters.

Eliasson and Mattsson (2006) develop a method for detailed and quantitative assessment of equity effects of road pricing by taking into account changes in travel behaviour and how revenue from road pricing is used. Our study is inspired by their study and fundamentally follows their methods. It also aims to assess the application to commuters' airport surface access strategy to change commuters' travel behaviour in order to reduce carbon emissions produced during their commuting. The quantified results provide sufficient evidence to merit exploring the mitigation measures by focusing on the equity effects of the carbon abatement instrument on different groups.

Manchester Airport is chosen because it is a relatively large airport with good direct rail and motorway links in the UK. However, the share of public transport use among employees (5% in 2005) is small compared with other large UK airports, such as London Gatwick (11.3%) and Heathrow (6%). The public transport usage by commuters has decreased even after the implementation of the ASASs proposed by Manchester Airport. The ASAS of Manchester Airport targeted 20% of the public transport share of commuters in 2005 and 30% in 2015, which requires drastic action if the target is to be achieved. Therefore, it can act as a good example for exploring opportunities to encourage changes in commuters' travel behaviours, shifting from car travel to other modes such as public transport, walking and cycling.

The remainder of this paper is structured as follows. Section 2 explains the methodology, models and data used. The current travel mode share and amount of carbon emitted by commuters are examined by using Manchester Airport as a case study in Section 3. The quantified equity effects of a carbon charge and an assessment of the impact of distribution on user group are presented in Section 4. Scenario analysis is conducted and discussed to explore the impact of carbon charge differences in Section 5. Section 6 concludes with findings and a discussion of the results.

2. Methodology and data used

To evaluate the equity effects of a carbon charge on car users, it is necessary to estimate the carbon footprint of each commuter and the damage costs of CO_2 emissions by commuters on airport surface access. The net welfare impact of the carbon charge then depends on (1) the change in travel pattern and (2) how revenues are used (Eliasson and Mattsson, 2006). In other words, the issue of equity deals with how different groups benefit from the use of carbon charge revenues. The change of travel mode share due to the impact of the carbon charge on travel cost is estimated by using a multinominal logit model (MNLM). Then, the net effect of carbon is estimated.

The analysis uses the data from a staff revealed preference survey carried out by Manchester Airport carried out from 2008 to 2010, which aims to understand the commuters' mode of travel preference at Manchester Airport. The survey was conducted by the Airport Surface Access Strategy department of Manchester Airport as a part of their programme of 'Airport Surface Access Strategy' in order to encourage the use of public transport by commuters, which was suggested by the UK government (Airport Surface Access Strategies, Department for Transport (1999)). The survey sample size is 3,290, and was conducted over three years from 2008 to 2010. Data include individual trip profiles, which consider the origin of the trip by postcode, trip mode, type of work (shift or non-shift), gender, age, the time of start and finish of the work day, job type (the name of the job) and employer name. Travel modes are segmented into eight categories: (1) car alone, (2) car with a passenger, (3) passenger in a car, (4) taxi, (5) bus, (6) metro, (7) cycling and (8) walking. Based on the postcode data of the individual trip, distances from the departure points to the airport (the location between Terminals 1 and 2) and vehicle journey time can be estimated by using GIS. Then, fuel consumption per individual on each route is estimated to compute the travel cost for car commuters in British pounds. Next, the total amount of fuel consumed can be converted into the total CO_2 produced on the trip.

Furthermore, several interviews were conducted with airport surface access strategy managers and employees at Manchester Airport in 2011, together with site visits to gain an in-depth understanding of the location and facility arrangements of the airport and establishing reasonable assumptions for analysis.

2.1 Modelling travel mode choice

Discrete choice models are widely used for estimating the impact of an attribute on market share. The marginal effect of the travel cost obtained from the model allows us to estimate the effect of the additional travel cost on car travel users. A property of the MNLM is the independence of irrelevant alternatives (IIA), which states that the relative probability of choosing any mode is independent of the presence of any other trip mode in the choice set. In other words, this is a weakness of the MNLM, because the IIA means that adding or deleting alternative outcome categories does not affect the odds among the remaining outcomes. For instance, the car-alone and car-with-a-passenger modes are more similar than bus and rail. The nested MNLM is adopted to address this issue.

The choice sets were modelled as the set of all modes available for the trip between the worker's residence and the airport. The models aim to express the share of commuters that chose each travel mode between departure/end points and the airport for a given day during 2008 and 2009. Two key parameters are selected: the total travel time for each journey and the total travel cost in pounds for each journey.

Standard car travel time is estimated based on the travel distance by GIS. This standard car travel time is used for all car travellers (car alone, car with a passenger, passenger in a car, and taxi) as their 'travel time' parameters; however, 20 minutes is added to the standard car travel time for train travellers. Bus speed is adjusted by a factor of 0.713 for computing bus users' 'travel time'. This factor was estimated based on the detailed analysis of modelling after observing the actual traffic movement in the Manchester Metropolitan Area (MMA) by the Greater Manchester Transport Unit (2009). Regarding a speed adjustment factor for walkers, 0.2 is used for walkers and 0.67 for cyclists, assuming that the walkers' speed is around 8 km per hour and the cyclists' is 12 km per hour. The marginal effect of the mean of the probability of choosing each mode with respect to a change in the travel cost of car travellers is estimated based on the results of the logit models. The estimated parameter is used for computing the impact of the travel cost change of car users on mode share.

Manchester Airport has three passenger terminals and one freight terminal, with two 10,000-foot runways. The train station and bus terminal are located between Terminals 1 and 2, and commuters' car parking is allocated on the other side of the terminal building from the station. In fact, the airport area is so large that it covers more than 16 km^2. Hence, each commuter's final destination at the airport varies and may be quite some distance from the train or bus station. In addition, some shift workers may not be able to use public transport due to the lack of service at certain times and others may not own cars or may not use a car due to the high price of fuel. Our data, however, do not include this information.

A two-level model problem is structured as a base model (Type 1 nest structure, see Figure 1) with one nest for car users (car alone, car with a passenger, passenger in a car, and taxi) and another for the four alternative mode choices (bus, metro, walking and bicycle). Another nest structure (Type 2) is grouped into three nests, which are (1) car (car alone, car with a passenger, passenger in a car, and taxi), (2) public (bus and metro) and (3) green (walking and bicycle). These groupings are based on the assumption underlying the model, which states that there is a correlation of error terms for car users.

Figure 1 to be inserted here.

We set the choice set to M nests $Nest_m$, m=1,.., M. Denote the nest to which alternative $j = 1,2, \ldots\ldots, J$ belongs as $Nest\ (m)$:

$$Nest\ (m) = \{Nest_m: j \in\ Nest_m,\ m = 1, \ldots M\} \text{ (eq. 1)}$$

For the nested logit model (NLM), the observed proportion of utility, which individual commuter i obtains from alternative j in the nest $Nest_m$, is decomposed into two parts: β_j is constant for all alternatives within a nest and V_{ij} varies over all alternatives within a nest. V_{im} is an equation that describes the nest. Hence, you have utility in the case of the Type 1 model:

$$U_{ij} = \beta_j + V_{im} + V_{ij} + \varepsilon_{ij} + \varepsilon_{im} \quad \text{(eq. 2)}$$

$$j \in Nest_m$$

$$i = 1,2, \ldots . N$$

$$\text{where } j = 1,2,3,4,5,6,7,8$$

$$m = 1, 2$$

$$V_{ij} = \epsilon_j + \gamma_{tj} Traveltime_{ij} + \gamma_{cj} Travelcost_{ij} + \gamma_{sj} Shift\ dummy_{ij} \quad \text{(eq. 3)}$$

where $Traveltime_{ij}$ is the total travel time by mode j of commuter i, $Travelcost_{ij}$ is the total travel cost by mode j of commuter i and $Shift\ dummy_{ij}$ is 1 when commuter i takes mode j for shift work, and 0 otherwise. Specifically, the utility of each mode is expressed as follows:

CAR nest ($m = 1$):

$U_{CA} = V_{car} + V_{CA} + \varepsilon_{car} + \varepsilon_{CA}$ (eq. 4)

$U_{CP} = V_{car} + V_{CP} + \varepsilon_{car} + \varepsilon_{CP}$ (eq. 5)

$U_{PA} = V_{car} + V_{PA} + \varepsilon_{car} + \varepsilon_{PA}$ (eq. 6)

$U_{TX} = V_{car} + V_{TX} + \varepsilon_{car} + \varepsilon_{TX}$ (eq. 7)

where CA is car alone, CP is car and parking, PA is passenger in a car and TX is taxi user.

Others nest ($m = 2$):

$U_{bus} = V_{others} + V_{Bus} + \varepsilon_{others} + \varepsilon_{bus}$ (eq. 8)

$U_{train} = V_{others} + V_{train} + \varepsilon_{others} + \varepsilon_{train}$ (eq. 9)

$U_{walk} = V_{others} + V_{walk} + \varepsilon_{others} + \varepsilon_{walk}$ (eq. 10)

$U_{bike} = V_{others} + V_{walk} + \varepsilon_{others} + \varepsilon_{bike}$ (eq. 11)

where bus is bus user, while train is metro user, walk is walking, and bike is cycling commuter.

Let the probability of choosing alternative $j \in Nest_m$ be equal to the probability that nest $Nest_m$ is chosen multiplied by the probability that alternative j is chosen, given that an alternative in $Nest_m$ is chosen:

$$\Pr(ij) = \Pr\left(\frac{ij}{Nest_m}\right) * \Pr(Nest_m) \quad \text{(eq. 12)}$$

$$j = 1,2,3,4,5,6,7,8$$

$$m = CAR, Others$$

where Pr $(ij|Nest_m)$ is the conditional probability of choosing j , given that an alternative in nest $Nest_m$ is chosen, and $\Pr(Nest_m)$ is the marginal probability of choosing an alternative in nest $Nest_m$ (Train, 2003). For example, $Pr(CA/CAR)$ is the conditional probability of choosing CA (car alone) given that an alternative in nest $Nest_{CAR}$ is chosen, and $Pr(CAR)$ is the marginal probability of choosing an alternative in nest $Nest_m$:

$$\Pr\left(\frac{ij}{Nest_m}\right) = \Pr\{\omega = j|\omega \epsilon Nest(m)\} = \frac{\exp(\frac{v_{ij}}{\theta m})}{\sum_{j \in Nest(m)} \exp(\frac{v_{ij}}{\theta_m})} \qquad \text{(eq. 13)}$$

where θ_m is the inclusive value parameter, which represents dissimilarity among all alternatives in the nest $Nest_m$, as a mutual correlation measure of the error terms of all alternatives within the nest. This is bounded by zero and one. The utilities are normalised by the inverse factor of θ_m for this nest. The denominator of eq. 13 represents the attractiveness of $Nest_m$. The log of this expression for each nest is called the inclusive value Γ_m, which can be computed from the log of the sum of the exponents of the nested utilities as below:

$$\Gamma_m = log \sum_{j \epsilon Nest_m} \exp(\frac{V_{ij}}{\theta_m}) \quad , 0 < \theta_m \leq 1 \qquad \text{(eq. 14)}$$

where Γ_{CAR} represents the expected value of the maximum utility of car alone, car with a passenger, passenger in a car, and taxi, and Γ_{Others} represents the expected value of the maximum utility of bus, train, walking and cycling. The expected utility of the CAR group alternatives equals Γ_{CAR} multiplied by the log sum parameter, θ_{CAR}, plus other alternatives common to the pair of alternatives, θ_{CAR}. If θ_m= 1 for all m, the NLM collapses to the MNLM (Ben-Akiva and Lerman, 1985):

$$\Pr(\omega \epsilon Nest_m) = Pr\{\omega \epsilon Nest(j)\} = \frac{\exp(\theta_j \ \Gamma_j)}{\sum_{m=1}^{M} \exp(\theta_m \ \Gamma_m)} \qquad \text{(eq. 15)}$$

The probability of choosing the nested alternatives can be obtained by multiplying the conditional probability of the nested alternative by the marginal probability as follows:

$$\Pr(\omega = j) = \Pr(\omega = j | \omega \epsilon Nest_m) \times \Pr(\omega \epsilon Nest_m) = \frac{\exp(\frac{v_{ij}}{\theta m})}{\exp(\Gamma_m)} \times \frac{\exp(\theta_j \ \Gamma_j)}{\sum_{m=1}^{M} \exp(\theta_m \ \Gamma_m)} \text{(eq. 16)}$$

The direct effect of $Travelcost_{ij}$ on the probability of choosing mode j given the nest m is

$$\frac{\partial \Pr(\omega = j | \omega \epsilon Nest_m)}{\partial Travelcost_{ij}} = \frac{\gamma_{tm}}{\theta_m} \Pr(\omega = j | \omega \epsilon Nest_m)[1 - \Pr(\omega = j | \omega \epsilon Nest_m)] \text{ (eq. 17)}$$

$$\forall j \in Nest_{m,} m = 1,2$$

where γ_{tm} is the coefficient of the variable $Travelcost_{ij}$ in the nest m.

The elasticity is obtained by multiplying the marginal effect by the ratio of $\frac{Travelcost_{ij}}{\Pr(\omega=j|\omega \epsilon Nest_m)}$. The estimated results are discussed in Section 3.

2.2 Fuel consumption for various travel modes

The calculation methodology for fuel consumption per trip (FC) in the case of car travel is explained in this section. The amount of fuel consumed in surface access by each journey is computed by using the following equation (Miyoshi and Mason, 2013):

$$FC_{ir} = EF_{ir} * d_r \quad \text{(eq. 18)}$$

where FC_{ir} is the fuel consumption (g) for vehicle i on route r, and d_r is the route distance in km on route r. EF_{ir} is the fuel consumption factor of vehicle i in grams (g) of fuel per km/h (kilometre per hour) on route distance d_r. EF_{ir} is computed based on vehicle engine power, type of fuel (petrol or diesel) and vehicle type. The fuel consumption factor of vehicle EF_{ir} is specifically established in the MMA. The standard fuel consumption factor of a vehicle in the UK is taken from a UK study by the National Atmospheric Emissions Inventory (NAEI) (Barlow and Boulter, 2009; NAEI, 2009). Then, the average speed functions for each vehicle category and emissions are computed, as expressed in the following general equation:

$$EF_v = [a + b.v + c.v^2 + d.v^e + f.ln\,(v) + gv^3 + \frac{h}{v} + \frac{i}{v^2} + j/v^3].x \quad \text{(eq. 19)}$$

where EF_v is the emission factor expressed in g/km with the average speed v; v is the average vehicle speed in km/h; and a to j and x are coefficients.

This is based on the assessments for Euro I and II vehicles given in the Transport Research Laboratory Database of Emission Factors (Barlow and Boulter, 2009). We estimate the fuel consumption factor of vehicles by engine power (less than 1.4 litre, greater than 1.4 litre but smaller than 2 litre, and greater than 2 litre), type of fuel (petrol or diesel), vehicle type produced by year (e.g. pre-ECE (Economic Commission for Europe), ECE15, EURO I and EURO II, etc.) and vehicle speed.

The fuel consumption factor by speed is weighted as a default fuel factor in the MMA, based on the vehicle fleet composition of the MMA obtained from 'The Greater Manchester Emission Inventory 2006 update, GMTU Report 1530', carried out in 2009. Table 1 shows the vehicle fleet composition in the MMA.

Table 1 to be inserted here.

Finally, the fuel factors by automobile type (e.g., car, taxi and bus) are estimated by combining the above vehicle fleet composition in the MMA with the data from NAEI (2009). Detailed calculation methodologies are discussed in Miyoshi and Mason (2013).

'The Greater Manchester Emission Inventory 2006 update, GMTU Report 1530' (2009) adopted the concept of 'bus speed adjustment factors' to take into account that buses stop more frequently and travel more slowly than other road vehicles. In this study, a bus speed adjustment factor of 0.713 is taken from the above report (Association of Greater Manchester Authorities, 2009). For example, if a car drives at an average speed of 40 km per hour on a given route, it is assumed that a bus travels at 40 × 0.713 = 28.5 km per hour. In terms of load factor, a figure of 12.4 passengers per carriage is taken from the UK national average (Association of Greater Manchester Authorities, 2009), since the average bus occupancy of the MMA is not available.

Next, CO_2 emissions are calculated by the factor of carbon content in the fuel. One litre of petrol yields 2.28 kg of CO_2, while 3.31 kg of CO_2 is produced by burning one litre of diesel oil. Thus, 2.51 kg CO_2 per litre is used as the default factor based on the composition of fuel type used in the MMA. Regarding the load factor in a car, one occupant is adopted for ‘car alone’ and two for ‘car with a passenger’, ‘passenger in a car’ and ‘taxi’. A factor of 42.5 g/pkm is used for metro, based on data from the Association of Greater Manchester Authorities (2009). This simplification is due to data limitations about the actual load factors of each metro used for surface access at Manchester Airport.

A fuel price of £1.083 per litre is established from the average petrol price in 2009, expressed in pounds (RAC, 2010). In addition, £0.3328 per km (AA, 2010) is included in car users’ travel costs as running costs, excluding ownership cost, according to the distance of each journey. The sample comprises 1,645; the total number of employees was approximately 18,000 in 2009.

2.3 The equity impact of the carbon charge

Previous studies regarding the equity analysis of road pricing or congestion charges have examined the different benefits for various groups – mainly high-income or low-income groups. When we consider a carbon charge on car users of airport surface access, assuming it has the same role as road pricing, the addition to car users’ travel costs affects travel behaviour. This is also related to political acceptability, equity, economic impact and effectiveness (Santos et al., 2010). The following impacts of a carbon charge are considered in this study:

1) Higher travel cost for various transport modes;
2) Modal change due to higher travel costs for car commuters;
3) Change in the total amount of the damage costs of CO_2 due to the change in the share of travel mode;
4) Distribution of carbon charge revenues.

For the equity analysis, it is particularly important to investigate how charge revenues are used (Button and Verhoef, 1998; Small, 1983). Revenues can be distributed in several ways, for example:

1) Revenues are split evenly between all commuters;

2) Revenues are split according to the amount of the damage costs of carbon;
3) Revenues are used to subsidise commuters' costs;
4) Revenues are used to improve public transport or other green commuting facilities in order to promote their use.

This study examines two cases in order to clarify the direct impact on each user by taking into account the damage costs of carbon produced by each traveller: (1) revenues are split evenly between all commuters and (2) revenues are split according to the damage costs of carbon. In order to estimate the welfare change, the following equation is used. This equation is adopted from the work on the impact of congestion charges carried out by Eliasson and Mattsson (2006).

Assuming an individual commuter i travels to the airport by using travel mode j,

$$\Delta Wij = -\sum_j P_{ij}^1 C_{ij} - \frac{1}{2}\sum_j (P_{ij}^0 - P_{ij}^1) C_{ij} + \frac{1}{2}\sum_j (P_{ij}^0 - P_{ij}^1) Carbon_{ij} \text{ (eq. 20)}$$

$$j = 1,2,3,4,5,6,7,8$$

where

ΔW_{ij} is the welfare change for individual commuter i using travel mode j,

P_{ij} is the probability of the trip from i using mode j,

C_{ij} is the cost of the carbon charge on the trip of i using mode j,

$Carbon_{ij}$ is the damage costs of carbon on the trip of i using mode j,

0 denotes 'before the carbon charge scheme',

1 denotes 'after the carbon charge scheme'.

We use the ‘rule of half’, as consumer surplus averages half of the cost generated by the change (Eliasson and Mattson, 2006; Small and Verhoef, 2007). Hence, this equation consists of three components: $-\sum_j P_{ij}^1 C_{ij}$ as the total carbon charges paid, $-\frac{1}{2}\sum_j (P_{ij}^0 - P_{ij}^1) C_{ij}$ as the value of the changes in travel mode and $\frac{1}{2}\sum_j (P_{ij}^0 - P_{ij}^1) Carbon_{ij}$ as the value of the carbon saved due to the carbon charge.

3. Empirical analysis: Manchester Airport

3.1 Travel mode and carbon footprint by employee

Carbon emissions (g) per person per km (g/pkm) are used to estimate the damage costs of carbon by travel mode. First, the total amount of carbon emitted by the mode is computed. Then, the average amount of carbon emissions from a trip by that mode is obtained after dividing by the total number of trips per year. Furthermore, carbon emissions (g/pkm) are available when the total CO_2 on a trip is divided by the number of occupants in a vehicle and the average distance travelled by the mode.

The following assumptions have been made:

(1) The total number of employees is 18,000 (based on an interview with Manchester Airport).
(2) Each employee commutes to the airport 200 times per year.
(3) Each employee uses the same mode of transport every day.
(4) The sample mode share is used to estimate total emissions.
(5) The social damage costs of carbon is £76 per tonne (Department for Environment, Food and Rural Affairs, 2007).

Table 2 shows the results of the carbon footprint and mode share at Manchester Airport in 2009. Walking and cycling are the ultimate zero-carbon and environmentally friendly options for personal transport (Chapman, 2007). Fewer than 2% of total employees use cycling as their travel mode to the airport. The average distance travelled is 6 km. Most employees are shift workers, involved in areas such as ground handling, catering and cleaning. Those who cycle to work also do so for early morning shift work.

The majority of car users (car alone, car with a passenger and passenger in a car) commute in an area within a 20-minute drive by car. Although the MMA has a developed train network, car commuters form a large part of the travel mode (83%), including car-alone users (73%). The majority of participants work for Manchester Airport and Her Majesty's Immigration Office. The average CO_2 (g)/pkm of car-alone users is 152 g/pkm; however, this is reduced to 76 g/pkm in the case of car sharers, who account for some 10% of commuters, as a result of which their average emissions (g/pkm) are slightly lower than those of bus users. This shows the large impact that car-sharing schemes can have on emission reductions.

It will be challenging to persuade employees to change their travel mode from private car to public transport if they are involved in shift work at the airport (Budd et al., 2011). However, there is scope to change the behaviour of non-shift workers. Based on the data, the majority arrive around 8 o'clock in the morning and depart at 5 o'clock in the evening. This fact provides support for the potential for a car-sharing scheme for non-shift workers.

Table 2 to be inserted here.

3.2 Damage costs of carbon emissions by employee surface access

Several assumptions are required to estimate the damage costs of CO_2 emissions. Based on the assumption that all employees work 200 days per year, using the same travel mode for return, the total amount of CO_2 emissions becomes 15,640 tonnes annually. Thus, if the price of carbon is £76 per tonne according to Department for Environment Food and Rural Affairs (2007), the annual cost of CO_2 is approximately £1.2 million. This amounts about 11% of the CO_2 cost of the passenger surface access, which is £10.9 million based on our previous study (Miyoshi and Mason, 2013).

Table 2 shows that the cost of CO_2 becomes significantly lower when private car rides are shared. It should be noted that the cost of CO_2 involves some uncertainty as it is assessed over longer period (Department of Energy and Climate Change, 2010; Guo et al., 2006; Mayers et al., 1996). Even in a low-cost scenario (£25 per tonne), the total cost of CO_2 for car-alone users is over £39,000 per year – and £110,000 per year for the higher price (£76 per tonne) – for commuters at Manchester Airport.

The share of car-alone users is 73%, while this category accounts for 96% of the total amount of CO_2 emissions produced. The annual climate change costs at Manchester Airport in 2009 were £82 per employee for car-alone users compared with £37 per employee for car users with a passenger, £24 per employee in the case of a passenger in a car, £33 for a taxi, £17 for a bus and £26 for a train user. Thus, as a result, the climate change cost in 2009 was £45 per employee using private transport. The damage costs of carbon by car-alone users is only 41 pence per trip. The damage costs of CO_2 by car-alone users is, however, significantly larger than others, in particular when the carbon price is higher. Society, then, pays more than £60 per employee per annum to car-alone users compared with commuters using public transport.

The effect of the travel mode switch from private to public on the overall cost of CO_2 is large. For instance, if 10% of car-alone users change their mode to metro, 1,427 tonnes of carbon could be saved annually, which is equivalent to a carbon saving of more than 9%. Given that a large proportion of CO_2 emissions are produced by private car users, the cost of CO_2 will be reduced if the number of private car trips decreases through a carbon charge on car users or car-sharing for airport commuting. In particular, the impact of an abatement scheme on the CO_2 cost becomes greater when the CO_2 price is higher. In addition, the reduction of car users will help reduce other externalities, such as congestion and air pollution around the airport.

3.3 Effects of the travel cost increase on travel mode share

Two pounds is charged to all car users except taxis for each return trip, taking into account that the damage costs of a car trip is about £0.8 per return trip and the fact that major airports charge £2 for passenger drop-off at the airport. It is assumed that car sharers, such as a car with a passenger and a passenger in a car, share the charge equally. We also assume that the total number of trips is not affected by the carbon charge resulting from the commuting trip.

Several logit models are constructed to estimate the impact of the travel cost increase on the change of mode share. Three parameters are used: total travel time in minutes per way, total travel cost in pounds per way and the shift dummy 1 for shift workers and 0 otherwise. The estimation is conducted by using STATA 12 (Heiss, 2002). The results of the preferred MNLM and RUMNL models and the estimation results of each model are presented in Tables 3 and 4. The estimated results are used for the equity analysis in a later section.

Firstly, we evaluate whether the MNLM should be replaced by a NLM. The rho-squared value of the MNLM shows the overall goodness of fit of the model ($rho^2 = 0.52$), as well as the log likelihood test result (−823.24). The Hausman test is conducted to test the independence of the irrelevant alternatives (IIA) assumption. The test statistic is significant, which rejects the IIA assumption by indicating that the MNLM is not appropriate. (Koppelman and Wen, 1998). The log likelihood for the IIA test statistic of model 1 (the base model of the NLM) also suggests the strong rejection of the MNLM in favour of the NLM.

Tables 3 and 4 to be inserted here.

We choose the model and tree structure according to the overall goodness-of-fit measure (the log likelihood at convergence) and compliance with global utility maximisation (Hensher et al., 2005). In addition, the signs of parameters are considered. Only the RUMNL model 2 satisfies the required condition with global utility maximisation by presenting that all log sum values are between 0 and 1. The signs of all parameters are negative except taxi (z =0.52). The parameters of car alone and taxi are not significant. The other parameters are statistically significant by showing a value of travel time (VOT) between £10 and £19.8 per hour. A walking commuter’s VOT is the lowest (£10.4), as expected, while that of a bus traveller is highest (£19.8 per hour/£2.78/km at the 28.7 km/h moving speed). This is due to the high cost per trip compared with the relatively short travel time. Car-alone users' VOT is only £2, but this is not statistically significant. The VOTs of car sharers are estimated as £17.6 per hour (£1.09/km) for a car with a passenger, which is a two-occupant automobile moving at 48.5 km per hour, and £19.4 per hour (£1.91/km) for a passenger in a car (two occupants) driving at 47 km per hour. The estimated average marginal effects of the carbon charge based on the results of RUMNL 2 are used in the next section to assess the equity differences among user groups.

4. Equity effect of the carbon charge for different groups

In this section, we investigate the equity difference among commuters by using a case of a £2 charge per return trip. To assess the equity impact of a carbon charge, three elements are considered:

(1) Net effect only of the carbon charge (£2 per return trip),

(2) Net effect including distribution: the change of travel mode share through the carbon charge (£2 per trip) and the revenue from the carbon charge are equally distributed,

(3) Net effect including distribution: the change of travel mode share through the carbon charge (£2 per trip) and the revenue from the carbon charge are distributed after deducting the damage costs of carbon by each commuter. This distribution highlights the incentive to greener commuters, based on the damage costs produced by each commuter.

The impact of a carbon charge on the different groups is estimated by using the methods explained in Section 2.3. The change in commuters' welfare by implementing the carbon charge is separated into three categories (carbon charge, value of travel mode change and the damage costs of carbon) and compared by four categories: (1) travel mode group, (2) gender, (3) job type and (4) age group. The results are shown in Figures 2 to 9 and Table 5.

Table 5 to be inserted here.

Significant value of travel mode change is not observed due to the low average marginal effects of the carbon charge compared to the amount of carbon charge, based on the results of RUMNL as well as changes in carbon cost. Hence, the effects of the carbon charge are mainly shown in the outcome in the case of the £2 charge in this section. However, approximately 9.3% of commuters changed their mode from car to other modes due to the carbon charge.

Approximately £5.1 million can be generated as revenue from a carbon charge; £281 can be split evenly between individuals per annum. We also see the impact of a carbon charge when taking into account the damage costs of carbon produced by each travel mode. This is simply based on the concept that each traveller needs to compensate the damage costs based on the amount of carbon emitted by individual travel. The carbon charge is imposed only on car users.

Altogether, £83,355 per year is shown in terms of the carbon costs saved from the carbon charge. The total net welfare for all commuters is –£5.0 million, while the revenue for the airport due to the total carbon charge could be £5.06 million. Airports could use this £5.06 million to improve their facilities to promote low-carbon commuting, or by distributing this cash to individual commuters directly. The welfare by individual can be analysed based on the distribution to those individuals.

(1) Travel mode group

Figures 2 and 3 show the results of the analysis. The net welfare for car commuters is negative due to the carbon charge, whereas it is positive for other commuters. The positive value of other commuters' travel mode changes clearly shows the impact of a carbon charge on a mode shift, from car to other modes. The result, however, looks different when the revenue from the carbon charge is distributed equally (£281per commuter). The net welfare of all commuters, except car-alone users (−£124), increased positively to between £45 and £328.

When the damage costs of carbon produced by individuals is considered in terms of revenue distribution, it could be distributed to employees in the range of £260 (car-alone users) to £343 (walkers and cyclists) per individual per year. As a result, public transport users (£326 for bus users and £316 for metro), walkers and cyclists (£343) gain more benefit than all car users.

Figures 2 and 3 to be inserted here.

Most commuters, except car-alone users (−£146), can receive a positive benefit from a carbon charge. Public transport travellers receive more than £316 in benefit, which can be used for their travel expenses; the benefit can be used as a direct incentive for those who commute by walking or cycling.

(2) Gender, age and occupation type groups

The majority of the sample travels by car alone – accounting for 73% of total commuters, split into 43% male and 30% female – while 4% opt to walk or cycle and 12% use public transport. In fact, women travel more by car and less by public transport, walking or cycling. This is a different result from other road pricing studies that have focused on city centres (Raje, 2003; Santos, 2004). Therefore, the net effects of the carbon charge and distribution show that women receive less benefit than male commuters (see Figures 4 and 5).

Figures 4 and 5 to be inserted here.

Younger and older groups gain more benefits compared with other age groups (see Figures 6 and 7). This is because cyclists consist of mainly the younger generation, while the older group consists of relatively more walkers. There is also a relationship with the job type groups: 80% of cyclists and walkers are in the ‘retail and catering’, ‘cleaning and building maintenance’ and ‘handling agent’ groups, who work shifts in the sample studied. More than

56% of bus travellers are also in these groups, while the ‘administration’ job group travels more by train. In particular, 46% of the ‘cleaning and building maintenance’ group travel via a non-car mode, and this figure is 31% for ‘retail and catering’. The average travel distance of bus, walking and bicycle commuters is within 6 km. The total travel time might be shorter than that of driving a car when the extra time taken walking from the car park is considered. On the other hand, the travel distance for train travellers is 21 km on average. Most live in the Manchester city area to the north of the airport, and the average metro fare (£5 for return) is similar to the travel costs (£5.2 for return) of car-alone users.

The ‘retail and catering’ and ‘cleaning and building maintenance’ groups could receive more than £157 per year in benefit as a whole, although the executive and middle-management groups see a negative effect of £37–71 due to the carbon charge (see Figures 8 and 9). However, it should be noted that more than 45% of car-alone travellers belong to the airport operating job group (aircrew, engineer, handling agent and security). Those who use their car for shift work would not benefit from the carbon charge either (-£70 – -£24 per annum). Hence, other incentive methods should be considered to compensate those shift worker groups.

Figures 6, 7, 8 and 9 to be inserted here.

5. Scenario analysis (carbon charge change)

A scenario analysis based on the change of carbon charge is conducted to investigate the impact of changing the carbon charge The results are also used to explore which group is affected the most and what is a suitable level of charge.

Figure 10 presents the social welfare increase achieved through the carbon reduction based on this analysis. In the case of the £2 carbon charge, about 7% of carbon emission reduction is expected and this results in a £125,228 social welfare increase, including £83,355 carbon costs saved, as presented in the previous section. It also shows that more than £250,000 in welfare effects will be gained by the 16% reduction in CO_2 achieved through the carbon charge scheme.

Figure 10 to be inserted here.

However, some commuters' welfare could drop significantly according to the carbon charge to car commuters, if the revenue is not distributed (see Figure 11). Interestingly, the welfare changes for greener commuters, such as public transport users and walkers / cyclists are not so different, even if the carbon charge increases to £5 compared to that of lower charge.

Figure 11 to be inserted here.

Figures 12 and 13 show the change in the commuters' welfare through the revenue distribution as a result of the carbon charge. When the revenue from the carbon charge is distributed to commuters, greener commuters increase their welfare significantly, particularly if the carbon charge is high. Car commuters also see some benefit, however, carsharers' welfare becomes negative when the carbon charge exceeds £3.50 in the case of equal revenue distribution. The threshold becomes £4 when the revenue is distributed based on the damage costs of each commuter's mode of travel. Car sharers' welfare becomes maximum when the carbon charge is £2 per trip and when the social cost of CO_2 is £79 per tonne.

Figures 12 and 13 to be inserted here.

Car sharing is one of the important abatement options for mitigating CO_2 from airport surface access. Hence, in order to encourage car sharing as well as the use of public transport, it is necessary to provide the best welfare possible for car sharers. The results indicate that £2 could be an appropriate charge. Otherwise, other incentives for car sharers could be implemented. As a result, this will lead to a further reduction in the amount of emissions.

6. Findings and discussion

This study attempts to conduct an ex-ante analysis by quantifying the equity effects of a hypothesised economic instrument, ‘carbon charge on car commuters’, at Manchester Airport. The results suggest that travel mode behavioural change can be achieved directly by imposing a carbon charge on car commuters. The mode preference and attractiveness of car commuting are both significantly high for airport commuters in the current environment, yet the carbon charge can affect the travel mode change and lead to a carbon reduction. Positive effects for commuters who use less carbon, such as public transport users, cyclists and walkers, are observed when direct distribution is considered. Most of these users are the young and the older generation who have relatively low wage occupations at Manchester Airport.

Furthermore, ‘car alone’ is the travel mode used by the majority of the sample, and its users belong to the medium-income group. Hence, another scheme to provide additional incentives to car users should be implemented to compensate the majority group. One could be a car-sharing scheme, which generates extra revenue by selling to passengers car parking spaces vacated by previous car users. This revenue can be used as an additional incentive to attract car-alone commuters to car sharing. In addition, the results of the scenario analysis indicate that car sharers might lose their welfare when the carbon charge is high. In order to compensate this loss and encourage car sharing, other methods can be implemented.

On its own, a carbon charge on car users is not sufficiently effective to change car commuters’ travel behaviour. A combination of incentives (car-sharing scheme) and disincentives (carbon charge on car users) generates financial resources to provide transportation subsidies to public transport commuters or economic incentives for non-carbon travellers. Moreover, the monetary incentives generated by a carbon charge on car users can provide direct benefits for those travellers choosing public transport by offering additional capital and decreasing their

VOTs. This also helps prevent social exclusion as a minor traveller group among commuters at Manchester Airport.

Certainly, car commuters can be expected to object to additional costs being charged for their commute. In addition, if it is not properly supported or subsidised by the government in the UK case, the measure will not deliver a desirable outcome (Lucas, 2012). A car-sharing scheme can be less attractive for airports due to administration costs unless airports receive economic funding for the project from the government, such as tax reductions or other monetary incentives for subsidising the annual cost. However, revenues from carbon charges can complement each other. Further, they should be fairly and transparently distributed to each participant by considering the equity effects. Strategy- and policymakers are required to identify whether the projects offer potential Pareto improvements: projects for which winners could compensate losers, leaving all better off (Small and Verhoef, 2007).

Ultimately, a successful policy needs to consider three policy angles: (1) the need for competitive efficiency, (2) the need for geographical accessibility and social equity for all members of society and (3) the need for an environmentally sustainable development (Button and Nijkamp, 1997). A balanced policy involving monetary incentives and disincentives will be a key instrument in achieving the UK government's stringent targets and will promote social inclusion among the staff community at Manchester Airport. This study contributes by demonstrating quantitative evidence for this objective.

The analysis focused only on climate change costs in considering employees commuting to the airport. Other external costs, such as noise, air pollution, accidents and congestion, were excluded. In particular, the value of travel time of each commuter mode should be included for welfare estimation. This is a limitation of this study, and further research should include this. Moreover, private costs in terms of car ownership were not taken into account either. Needless to say, the total social cost of car users becomes more significant if all external costs are included.

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Table 1 Vehicle fleet composition in the Manchester Metropolitan Area in 2006

	Vehicle type produced		Engine power		Fuel type	
Car and Taxi	Euro I	12%	<2 litre	84.3%	Petrol	77.6%
	Euro II	88%	>2 litre	15.7%	Diesel	22.4%
Minicab	Euro II	100%	>2 litre	100%	Petrol	77.6%
					Diesel	22.4%

Source: Association of Greater Manchester Authorities (2009)

Note: Vehicle type of minicab is based on authors' assumption.

Table 2 Travel mode share, carbon footprint, and annual damage cost of CO_2 per employee at Manchester Airport in 2009

	Car alone	Car with a passenger	Passenger in a car	Taxi	Bus	Metro	Walking	Bicycle
Mode share before the carbon charge(CC)	73.2%	4%	6%	0.7%	8%	4%	2.3%	1.6%
Carbon emissions (g/pkm)	151.6	76.2	78.5	163.2	79*	42.5**	0	0
Average number of occupants	1	2	2	2	12.7	-	1	1
Average travel cost per trip	£2.16	£1.4	£0.36	£8.95	£1.25	£2.5	£0	£0
Travel time per trip (minutes)	22.2	20.6	13	10	15.2	44	46	25
Average distance (km)	17.9	16.2	10.2	6.4	7.17	20.5	6.2	5.9
The damage cost of CO2 per person and year at 2009 price	£82	£37	£24	£33	£17	£26	£0	£0

Note:* This value is estimated specifically for the Manchester metropolitan area in 2006 (source: Association of Greater Manchester Authorities, 2009).

**: This value is taken as a specific emission factor for Manchester Metro line (source: the Department for Environment, Food and Rural Affairs, 2010).

Table 3 Multinominal logit model: estimation result

Mode	Variables	Coefficient	St Error
Car alone	Travel time(min)	-0.6993**	(0.0519)
	Travel Cost (£)	25.66**	(2.8778)
	Shift	-0.9923	(0.8424)
Car in a passenger	Travel time(min)	-0.467**	(0.0519)
	Travel Cost (£)	22.843**	(2.8873)
	Shift	-2.07*	(1.037)
A passenger	Travel time(min)	-0.118**	(0.0317)
in a car	Travel Cost (£)	9.549**	(2.5617)
	Shift	-1.027	(0.7386)
Taxi	Travel time(min)	-1.041**	(0.2959)
	Travel Cost (£)	28.442**	(3.6697)
	Shift	-1.173	(5.2083)
Bus	Travel time(min)	-0.6186**	(0.5511)
	Travel Cost (£)	24.21**	(2.8834)
	Shift	-0.964	(0.8544)
Metro	Travel time(min)	-0.2657**	(0.4688)
	Travel Cost (£)	22.12**	(2.8670)
	Shift	-1.263	(0.9132)
Walking	Travel time(min)	0.0494*	(0.0246)
	Travel Cost (£)	-2.702	(3.2927)
	Shift	-1.173*	(0.6386)
Cycling	Travel time(min)	Reference	Reference
	Travel Cost (£)		
	Shift		
Log-likelihood			-823.24
Nr Observations			1644
			LR Chi2(21)=1794.44
			Pseudo R2=0.522

Note: Significance at 1 and 5% level is indicated with ** and *, respectively.

Table 4 RUMNL Model (nested logit model): estimation results

			RUMNM 1			RUMNM 2	
Mode	Variables		Coefficient	St Error		Coefficient	St Error
	Travel Cost (£)		0.0315	0.2016		-0.3166**	(0.0826)
Car alone	Travel time(min)		-0.1501**	(0.0575)		-0.0111	(0.0389)
Car in a passenger	Travel time(min)		-0.3869**	(0.1299)		-0.093*	(0.0405)
A passenger in a car	Travel time(min)		-0.3759**	(0.1205)		-0.1024**	(0.007)
Taxi	Travel time(min)		-0.7544*	(0.3949)		0.0517	(0.0994)
Bus	Travel time(min)		-0.2088**	(0.0416)		-0.1049**	(0.0325)
Metro	Travel time(min)		-0.1462**	(0.0341)		-0.0607*	(0.0239)
Walking	Travel time(min)		-0.0855**	(0.0144)		-0.0553**	(0.0086)
Cycling	Travel time(min)		-0.1516**	(0.02727)		-0.0836**	(0.0130)
Log-likelihood			-1696.36			-1684.94	
Nr Observations			13152			13152	
LR Chi2(21)=			3444.47 (p=0.000)			3467.33 (p=0.000)	
IV parameters							
		Car	1.602**	(0.5563)	Car	0.4947**	(0.1659)
		Others	1.187**	(0.28335)	Public	0.4701**	(0.1458)
					Green	0.04753**	(0.0365)
LR test of homoscedasticity (iv=1)			chi2(2)=0.95 (p=0.6226)			chi2(3)=23.8 (p=0.000)	

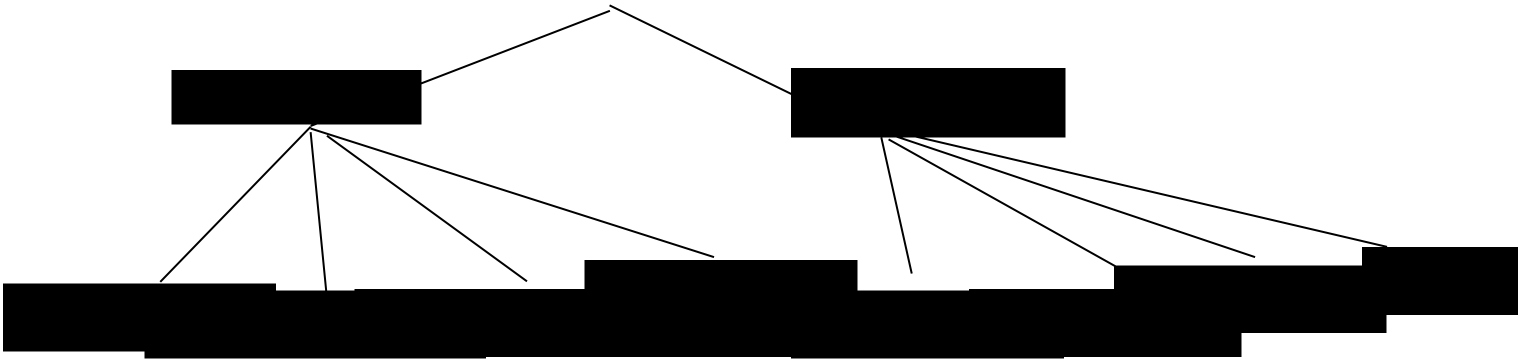
Note: Significance at 1 and 5% level is indicated with ** and *, respectively.

Table 5 Effect of carbon charge (£2) by travel mode group

	Car alone	Car with a passenger	Passenger in a car	Taxi	Bus	Metro	Walking	Bicycle
Mode share before the carbon charge(CC)	73%	4%	6%	0.7%	8%	4%	2.3%	1.6%
Average marginal effects of carbon charge	-0.033	-0.006	-0.006	0.0047	0.0185	0.0119	0.0055	0.0045
Mode share after the CC	66.6%	2.6%	4.9%	1.7%	11.8%	6.6%	3.4%	2.5%
Total charge paid per year	200	100	100	0	0	0	0	0
Net effect p.a. without distribution	-£406	-£237	-£221	£47	£29	£31	£33	£36
Value of distribution (per person and year)								
Revenues are split evenly	£281	£281	£281	£281	£281	£281	£281	£281
Revenues are split based on each damage cost	£260	£305	£319	£310	£326	£316	£343	£343
Net effect with distribution								
Revenues are split evenly	-£124	£45	£60	£328	£310	£313	£314	£318
Revenues are split based on each damage cost	-£146	£69	£97	£357	£354	£348	£376	£379

Figure 1 Nest structures

Type 1



Type 2

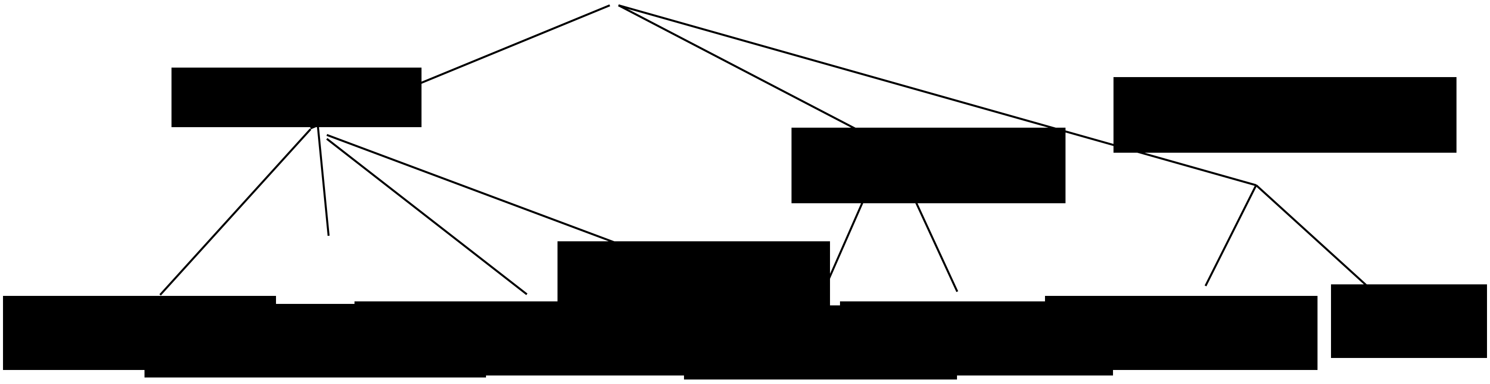


Figure 2 Commuters' welfare change by a carbon charge: Travel mode group

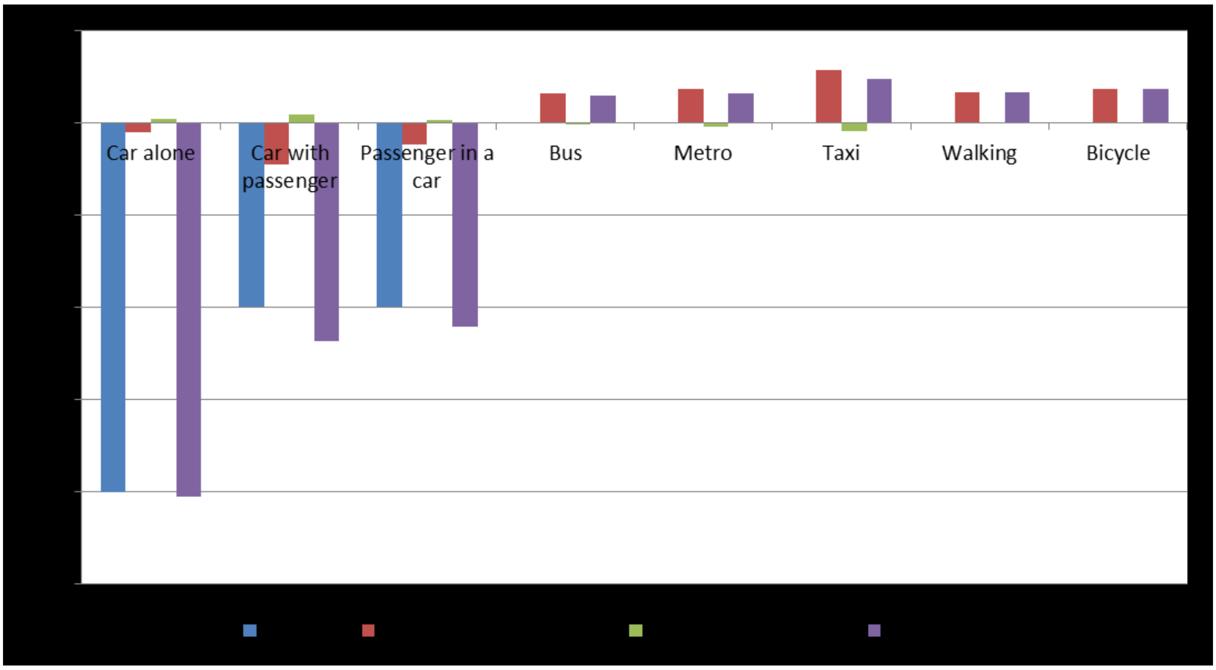


Figure 3 Commuters' welfare change by a carbon charge including the revenue distribution: Travel mode group

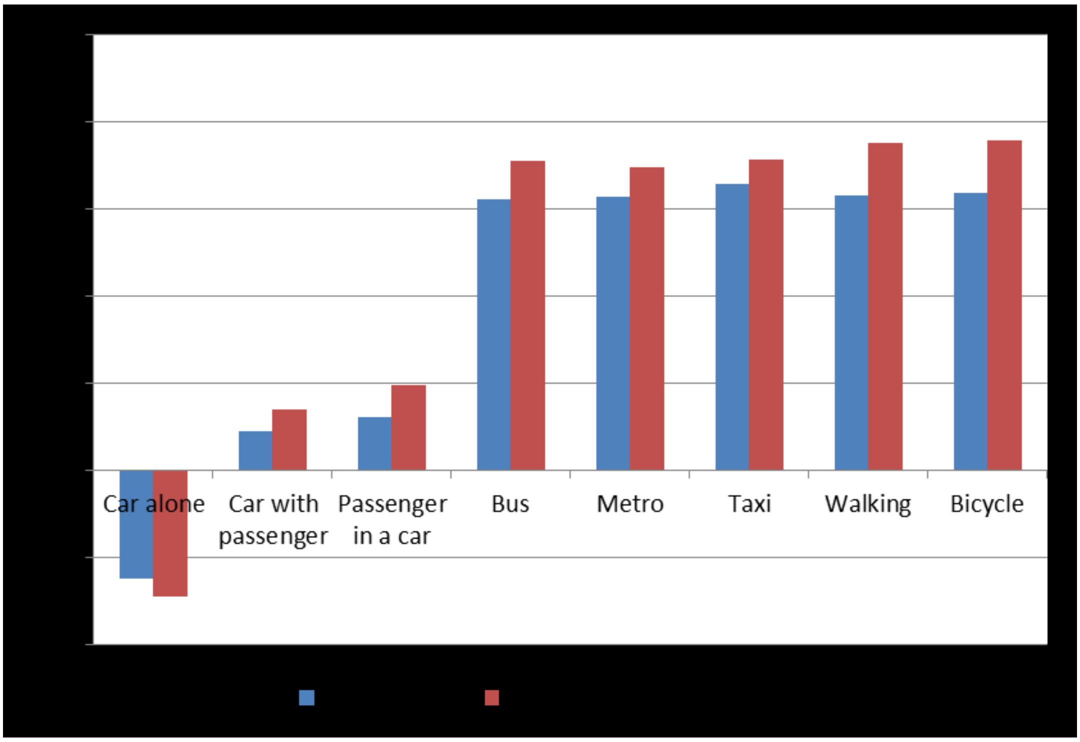


Figure 4 Commuters' welfare change by a carbon charge: Gender group

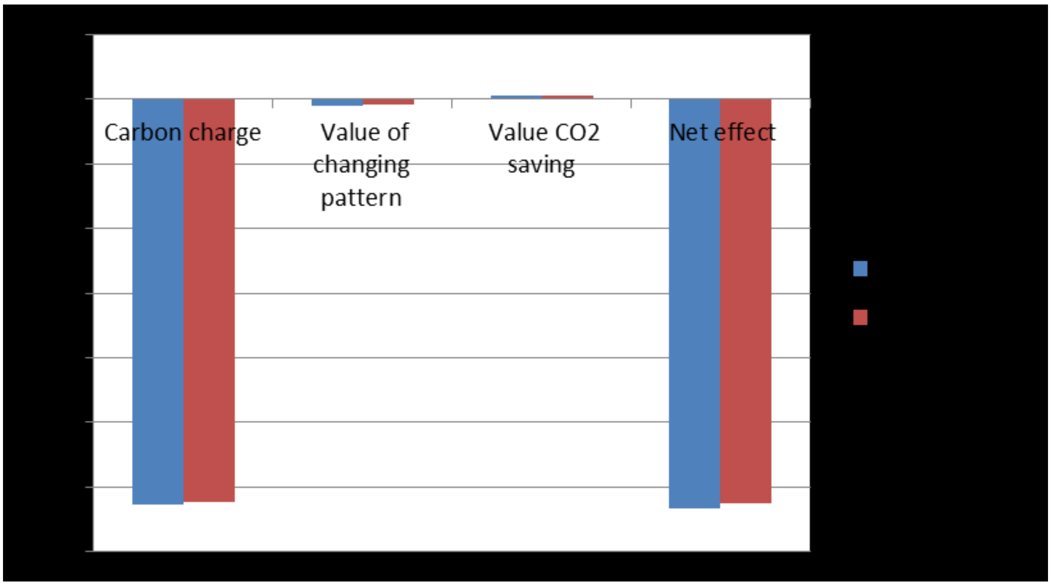
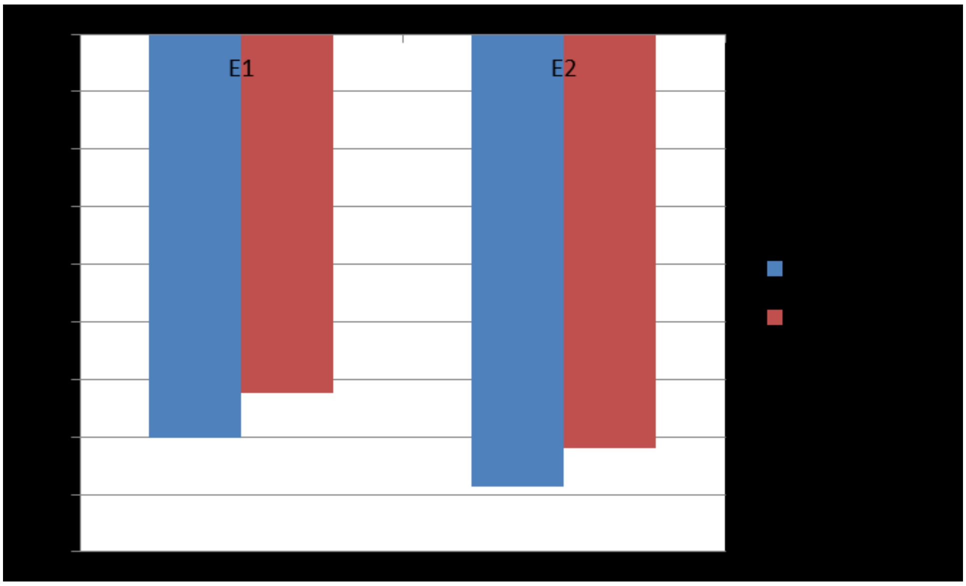


Figure 5 Commuters' welfare change by a carbon charge including the revenue distribution: Gender group



Note: E1 refers to the outcome of commuters' welfare change including the distribution without considering the damage cost by each user group, while E2 for the result of commuters' welfare change with considering the damage cost produced by each user group.

Figure 6 Commuters' welfare change by a carbon charge: Age group

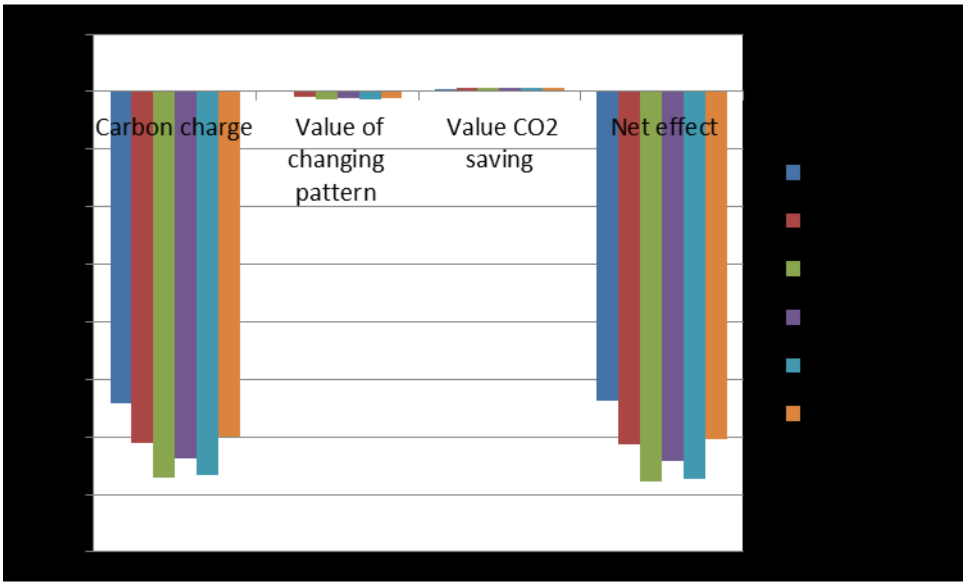
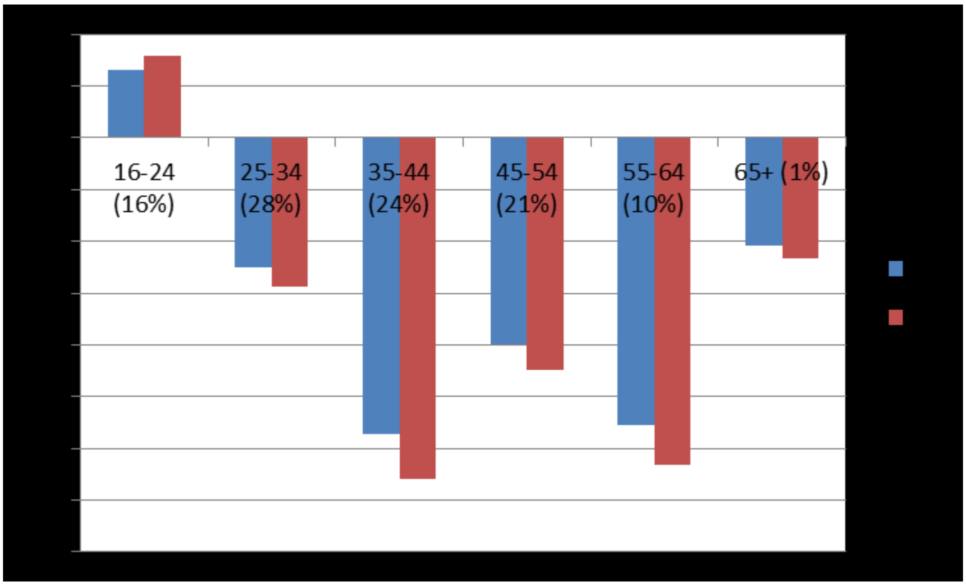


Figure 7 Commuters' welfare change by a carbon charge including the revenue distribution: Age group



Note: E1 refers to the outcome of commuters' welfare change including the distribution without considering the damage cost by each user group, while E2 for the result of commuters' welfare change with considering the damage cost produced by each user group.

Figure 8 Consumer welfare change by a carbon charge: Occupation type group

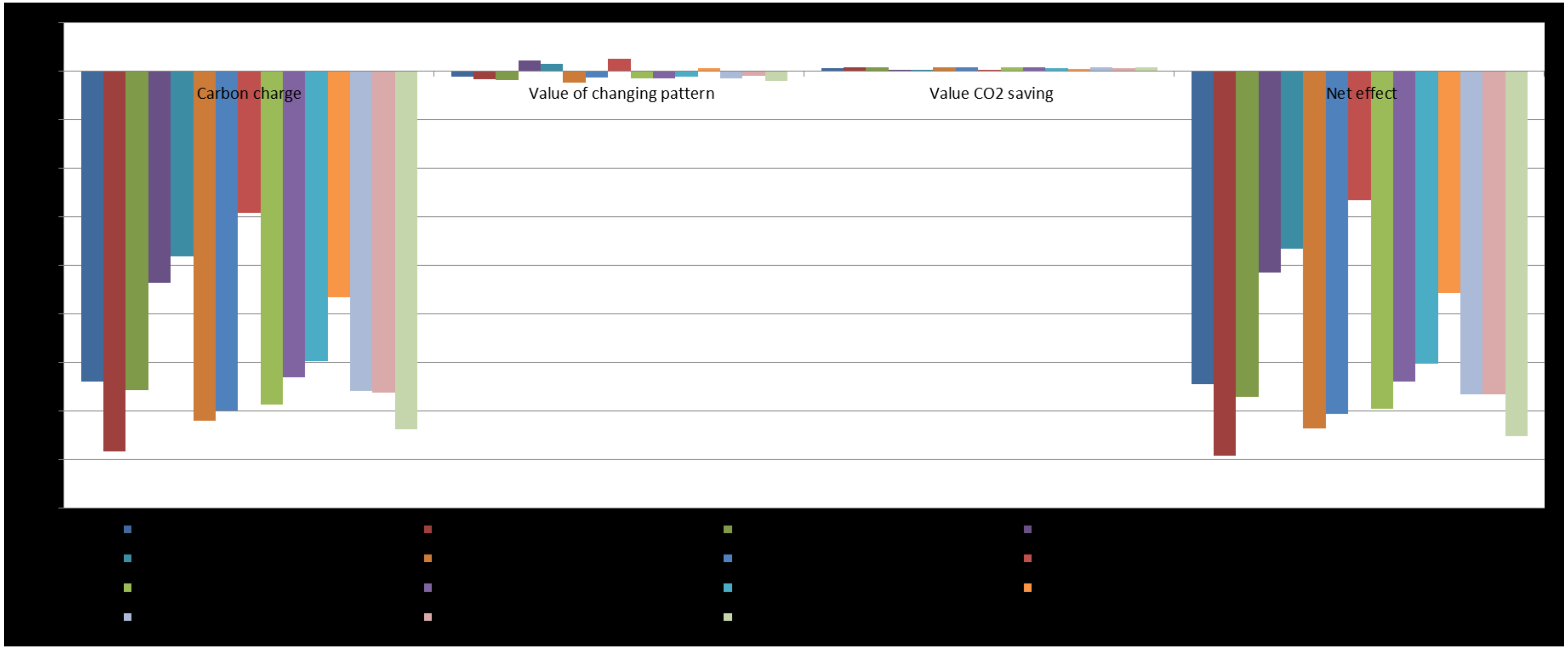
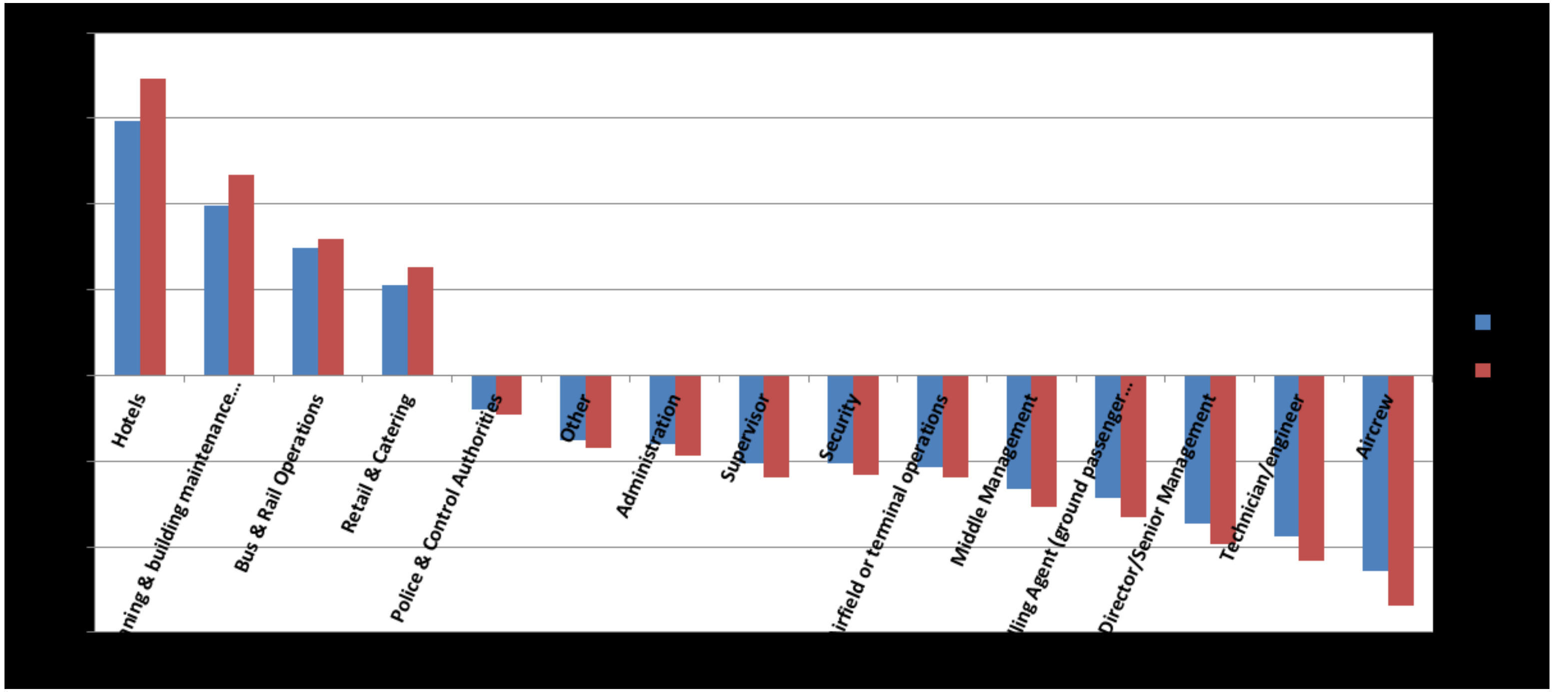


Figure 9 Consumer welfare change by a carbon charge including the revenue distribution: Occupation type group



Note: E1 refers to the outcome of consumer welfare change including the distribution without considering the damage cost by each user group, while E2 for the result of consumer welfare change with considering the damage cost produced by each user group.

Figure 10 Social welfare changes (£) and the carbon costs saved (£) by a hypothetical carbon charge to car commuters

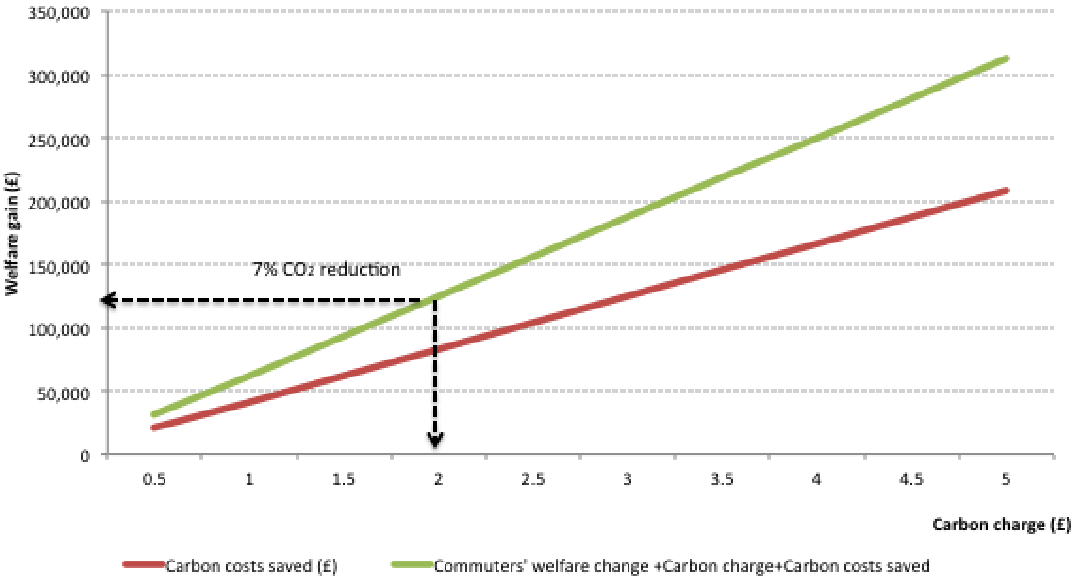


Figure 11 Commuters' welfare change by a carbon charge (£) without distribution

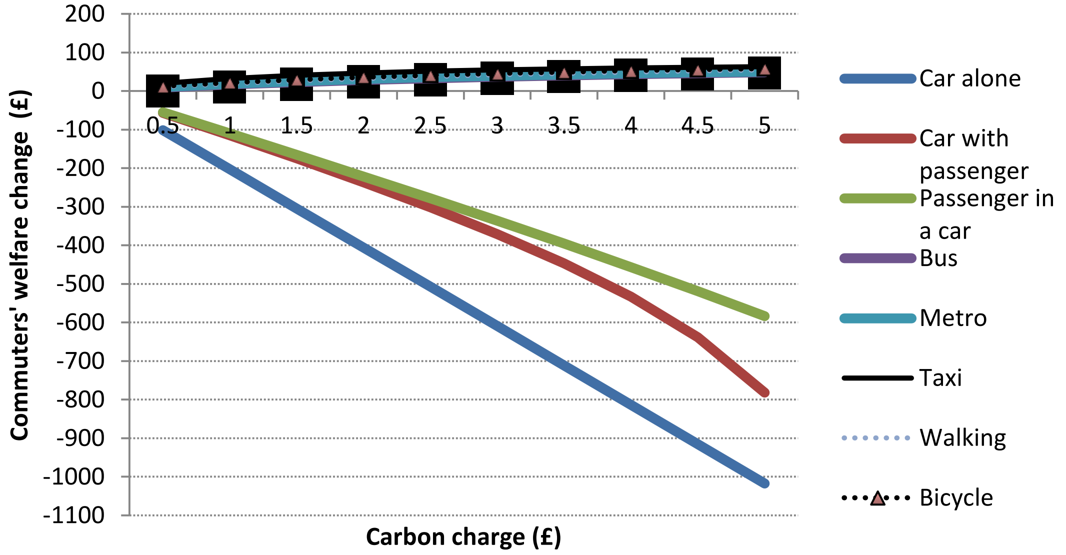


Figure 12 Commuters' welfare change by a carbon charge (£) with distribution

(Equally distributed)

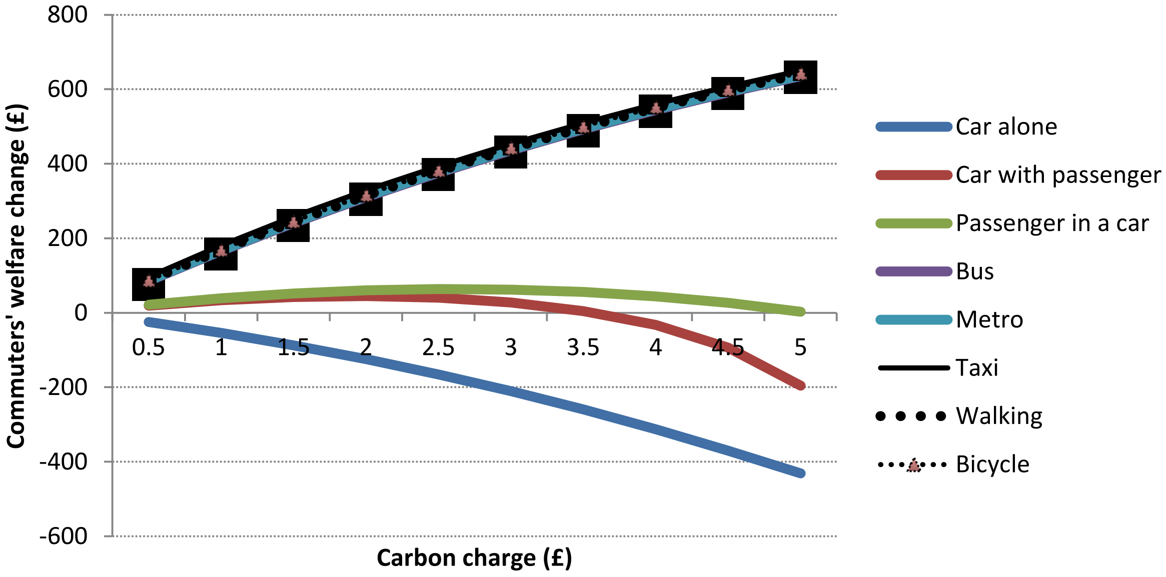
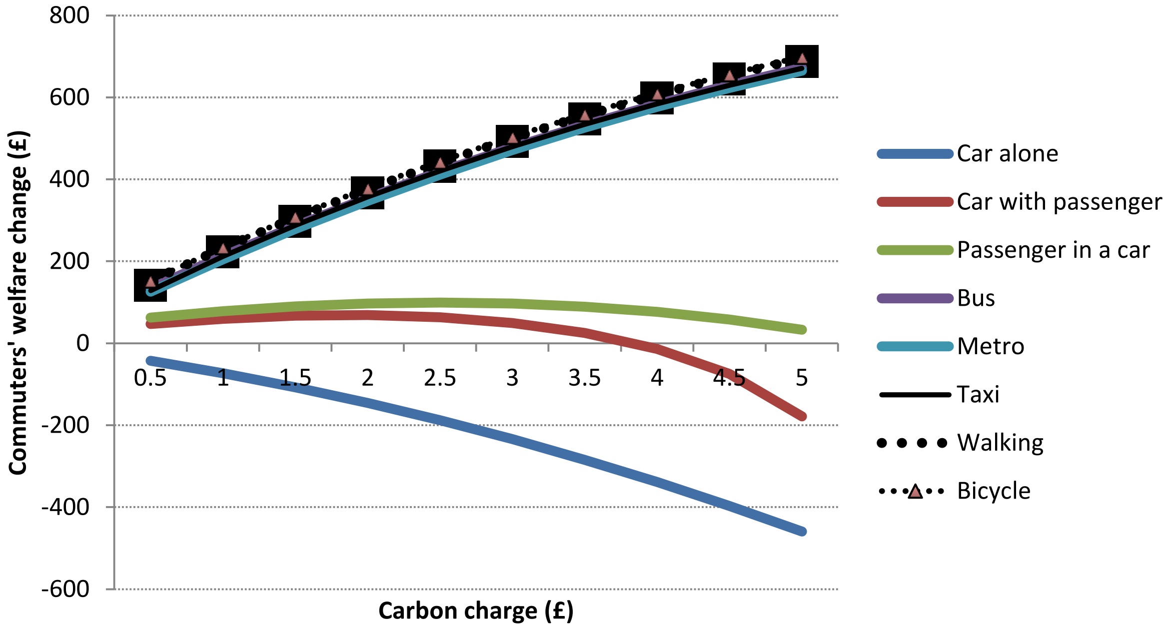


Figure 13 Commuters’ welfare change by a carbon charge (£) with distribution

(based on the damage cost of carbon by mode)



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