

Urban transport modal shift: an energy systems approach

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Abstract

Demand for transport services has increased rapidly over the last few decades, and continues to do so at a pace, particularly in specific developing regions. In view of the need to reduce carbon emissions whilst ensuring access to travel services, it is increasingly recognised that mitigation action needs to both promote low emission technologies but also consider other measures, including urban design, appropriate infrastructure development, and behavioural focused measures such as modal shift.

However, many energy models limit the role or even exclude behavioural measures. In this paper, we propose an approach to endogenising modal shift in a UK energy model, ESME. Focusing on urban passenger transport, the approach uses the travel time budget concept, explicit representation of infrastructure costs and incorporates non-motorised modes. Preliminary results show potential reductions in passenger demand of up to 15%, making a key contribution to cost-effective emission reductions. The modal shift level appears highly sensitive to the costs of car travel, and the travel time sacrifice (reduced mode speed) that is acceptable for urban passengers.

1. Introduction

The transport sector plays a critical role in enabling economic growth and facilitating consumer choices, around, for example, employment opportunities, where to live and how to spend leisure time. In the UK, demand for passenger transport has increased four-fold in the last 60 years, and has largely been driven by an increase in car ownership and use (Figure 1). Combined with freight transport, this growth in demand means that the transport sector is a key source of CO₂ emissions, accounting for 20%.¹

¹ UK Greenhouse Gas Inventory, 1990 to 2012. Annual Report for Submission under the Framework Convention on Climate Change. April 2014. <https://www.gov.uk/government/publications/uk-greenhouse-gas-inventory>

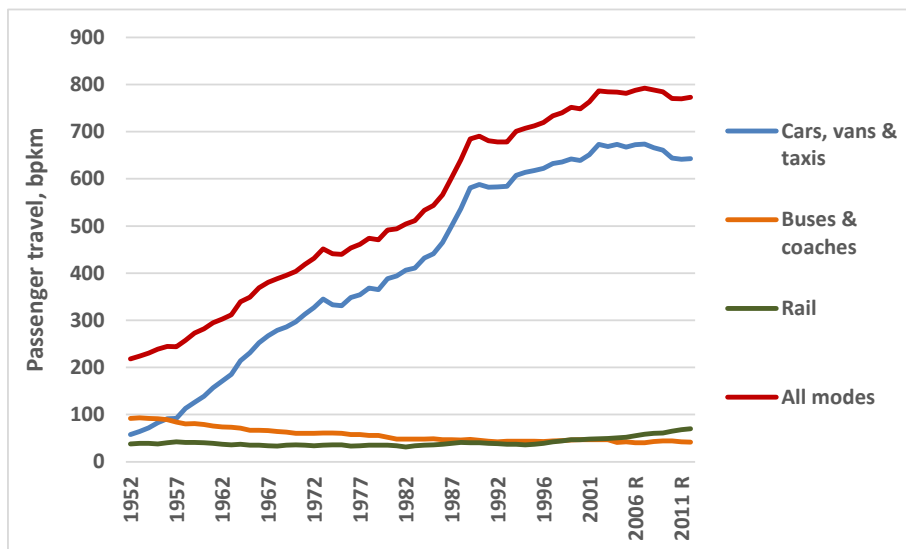
Tackling emissions in the transport sector is therefore imperative if the UK is to achieve its domestic emission reduction goals.

Many of the analyses around low carbon transitions have considered how the transport system could decarbonise in terms of technological transformation (DECC 2011, CCC 2013), and so-called E3 models² are typically used in such transition studies to map out decarbonisation pathways. Schäfer (2012) provides an overview of the types of demand side and behavioural measures that are incorporated into different E3-type models for the transport sector, and highlights their limited representation in bottom-up type optimisation models, whose focus is on technology and fuel deployment. The exception is price-induced demand response, which is typically incorporated in MARKAL/TIMES models, and in ESME (Pye et al. 2014).

While the large-scale uptake of low carbon technologies is clearly needed, significant opportunities exist for demand side orientated measures to play an important role (Goodwin 2007, Cairns et al. 2008, Gross et al. 2009, Anable et al. 2012, Daly et al. 2012). The lack of or simplified representation of demand side measures and behavioural change in many low carbon transitions pathways reflects both the ‘supply side orientation’ of the modelling tools used, and consequently there is lack of information to determine the extent to which such measures can contribute, or the extent to which behaviour and demand respond to differing pathways.

² E3 means energy system models that incorporate the following systems elements partially or comprehensively – *energy*, *economy*, and *environment*.

Figure 1. Terrestrial passenger transport demand by mode in the UK, 1952 - 2012



Source: TSGB 2013³

Building on methods developed by Daly et al. (2014), the paper describes how modal shift can be incorporated into a bottom-up energy systems model. It further develops the approach by applying it to a national systems model for the UK, focusing on urban transport, incorporating non-motorised modes and characterising infrastructure capacity and costs explicitly. The latter three issues are highlighted in Schäfer (2012) as particularly important elements of modelling transport sector behaviour in E3-type models.

This paper first describes the modelling of the transport system in energy models, in section 2. Section 3 introduces the ESME modelling framework used in the analysis, and describes the data assumptions and approach to implementation of modal shift. Section 4 presents the results of the analysis, followed by a discussion of the modelling insights and conclusions in section 5, and further research needs.

2. Transport sector and energy systems models

In this section of the paper we describe how the transport sector is modelled in energy system models, and how behavioural and demand side dynamics are included. We also review the evidence concerning the contribution of behavioural and demand side measures in contributing to transport sector emission

³ Transport Statistics Great Britain 2013, <https://www.gov.uk/government/statistics/transport-statistics-great-britain-2013>

reductions. Finally, we consider the issue of time budgets, and the implications of such a concept to modal shift.

2.1 Modelling transport behaviour in energy models

Schäfer (2012) suggested that the following specifications in E3 (Energy/Economy/Environment) models would be beneficial for assessing the impact of policies on behaviour change in transport. These include i) elastic transportation demand, ii) endogenous mode choice, iii) choice of no physical travel, iv) accounting for infrastructure capacity, and v) segmenting urban and intercity transport.

Bottom-up energy system models, particularly those with optimisation frameworks, are typically limited in representing any of these features, with the exception of elastic transportation demand, and some segmenting of urban demand (Loulou and Lavigne 1996). The baseline demands of individual modes are fixed, typically based on projections from transport sector forecasting models, so there inter-modal dynamics are not featured.⁴ Infrastructure costs are rarely incorporated while demand side choices that lower energy service demand, such as smarter choices or changing living patterns, are typically not considered. These models, such as those using the MARKAL/TIMES model generator, have strengths in terms of assessment of technology performance and costs. The question is how to improve the realism and extend the power of insight from these models by further incorporating behavioural features, and hence the motivation for this paper.

A number of other energy models, usually featuring a CGE framework, have made more progress in implementing features to model transport behaviour. The GCAM model (Global Climate Assessment Model) is a general equilibrium model that solves for prices, supply and demand across all markets. Mode choice is endogenously determined, based on cost of transport services (including fuel price) and wage rates (Kyle and Kim 2011). The Canadian Integrated Modelling System (CIMS), another hybrid model, integrates a discrete choice model for travel and vehicle choice, based on a multinomial logit model formulation (Horne et al. 2005). Another hybrid model capturing key transport sector behaviour

⁴ One approach to endogenising modal shift in MARKAL-type models is through the introduction of cross-price elasticities. One such example is a non-linearised elastic demand variant of MARKAL called MICRO (Loulou et al. 2004), although there is no evidence of its application for analysis in the literature.

is IMACLIM-R (IMPact Assessment of CLIMate policies-Recursive) which maximises a utility function, subject to travel budget constraints. Infrastructure investment is endogenous, where a reduced supply for a given demand leads to slower speeds, and feedbacks into the model (Waisman et al. 2013).

2.2 *The potential for demand side and behavioural measures in the UK*

A number of studies have considered the potential for demand side measures in the UK transport sector. However, with the exception of price-induced demand response, few techno-economic modelling studies incorporate such measures (as discussed above).

In their wide-ranging review of transport mitigation measures, Gross et al. (2009) concluded that there is significant potential for carbon reductions from changing behaviour patterns in the UK. This could be done in personal transportation through persuading people to reduce number of trips, switch modes and use cars more efficiently. Key measures include greater uptake of non-motorised modes (6% emission reduction relative to current road transport levels if comparable Northern European levels were reached), increased use of public transport, eco-driving (10-15% car emission reduction), use of smarter measures e.g. travel planning (5-10% car emission reductions) and road user charges.

Cairns et al. (2008) specifically focus on the potential of smarter choices. These are ‘soft’ initiatives designed to influence travel behaviour towards more benign and efficient options, through marketing, information and incentives, as opposed to measures that impacted on cost of travel or implemented technology-based solutions. Examples include work and school travel plans, improved public transport information, car clubs, car sharing and teleworking. The review concluded that national traffic levels could be reduced by 11%, and by 21% for peak urban traffic within 10 years, and that many such measures were cost-effective.

In a review of the literature for the Committee on Climate Change (CCC), Goodwin (2007) suggested that the evidence *is rich concerning reductions in car use up to about 20% or 30%, but sparse beyond that*. The review also highlighted that demand response may be limited in the short run but greater in the longer run, due to change in habits or changes in lifestyles. This difference in short and long run response is reflected in the literature on price elasticities, as highlighted in Goodwin et al. (2004).

Despite the established role that behavioural change can play, Anable et al. (2012) argue that the dominance of techno-economic analysis leads to a focus on technical solutions and carbon pricing. This is very much reflected in Government strategy documents (DECC 2011). While the strategy does state the importance of sustainable travel options such as public transport, cycling and walking, such measures are not given the same focus as technology-focused measures. In their paper, Anable et al. (2012) demonstrate the large impact that demand side measures can have using lifestyle scenarios that include both mode switching and demand reduction measures.

2.3 *Factors influencing behavioural change in urban travel choices*

Determining rates of possible future modal shift is a challenge, particularly a move away from cars to other modes. Historical trends over the last 30 years show the opposite, with increasing demand for car travel, at the expense of other modes. What this analysis envisages is that modal shift could play a role in reducing transport sector emissions, with a move towards a more sustainable transport paradigm (Bannister 2008). Many factors come into play in determining whether modal shift will be a realised emissions reduction measure, based on the cost and speed of modes as well as individual decisions, which are influenced by urban land use planning, infrastructure spend on large scale projects, investment in public transport and societal lifestyle factors.

At the level of the individual decision maker, a number of factors come into play. A shift in modes often results due to changes in circumstance e.g. place of employment or home, known as ‘churn’ (Goodwin 2007). Due to the mobility of the population (particularly in specific regions), this can happen frequently. Goodwin cites research by Dargay and Hanly (2003) which indicates that *over a nine-year period, over 50% of commuters change their main mode at least once. Of those who both move house and change employer during two consecutive years, 45% also change mode.* This highlights, that in given circumstances, mode switching does happen relatively frequently.

Other important factors around mode choice include habit (Schwanen et al. 2012) and access to information (Kenyon and Lyons 2003). Habits are not only negative but could reinforce sustainable transport behaviour. They may also be the function of a number of factors; not driven only by what is

considered rational (convenience, speed, cost) but also for other reasons, including lifestyle factors (Goodwin 2007). Kenyon and Lyons (2003) note that mode choice tends to be habitual but that information could inform mode choice, where it informs on comfort and convenience in addition to cost and duration. There is also an important role for demonstration of alternative to influence acceptance of alternatives (Bannister 2008). The role of affective (emotional) considerations is also gaining more prominence in relation to travel choices. Mann and Abraham (2006) highlight how car users often highlight the importance of autonomy, personal space and ownership / identity in their choice of mode. In addition to factors influencing individual choice, there are a range of location-specific factors that will also have a bearing on mode shift potential, namely land use planning, urban density and the location of housing and community facilities. The availability of and extent of different public transport systems is linked to urban planning. Local initiatives and policies targeted at different modes will also have a strong bearing on mode uptake. For example, there are measures aimed at dissuading motorised transport in urban areas e.g. London Congestion Charging Zone (CCZ),⁵ or at incentivising other modes e.g. the cycling initiative in the City of Portland, Oregon.⁶

2.4 Travel time budgets

The role of mode shift may be moderated by the concept of a travel time budget (TTB), that travel choices reflect an average daily travel time, and empirically that this is observed as relatively constant (and therefore stable, as proposed by Zahavi and Ryan, 1980). This concept is discussed here as it informs the modal shift approach described in the next section of this paper.

The reasons for this observed constant travel budget of around ~1 hour/day/capita is that *people have a certain amount of time that they are willing (or may even want) to spend on travel, and that they will make adjustments to minimize departures from that budget in either direction* (Mokhtarian and Chen, 2004). As the average speed of transport has increased, the apparent constancy of the time budget has remained intact, as distances travelled have increased. This time budget constant, however, is only observed at the aggregate spatial levels or the population as a whole. As soon as one starts

⁵ Further information on the London CCZ can be found at <https://www.tfl.gov.uk/modes/driving/congestion-charge>

⁶ *Portland Bicycle Plan for 2030*, <https://www.portlandoregon.gov/transportation/44597>. Portland is considered the most bike friendly city in the USA and has seen a rapid expansion in cycling in the past 15 years.

disaggregating populations e.g. age, gender, income etc., travel types and different spatial areas, large differences emerge (Mokhtarian and Chen, 2004). Therefore it seems that the net result of large differences across the population yield a constant budget, with higher TTBs being offset by lower TTBs. This offsetting leads some to question the very constancy of the aggregate time budget, as certain variables may change over time leading to changing TTBs (Goodwin 1981, in Mokhtarian and Chen, 2004). Some researchers have also pointed out that the data in some countries suggests non-constancy; van Wee et al. (2006) point to a slowly rising TTB in the Netherlands.

A key question is whether in the UK, a constant time budget would lead to increasing travel speeds and distances, as observed in the historic data. If indeed car travel demand is saturating, as suggested by Metz (2010), a constant TTB would require average speed to reduce. Otherwise, if demand decreases and speed remains constant, TTB would reduce. As described in the next section of this paper, TTB is used as a controlling mechanism to ensure that a broad mix of modes remain, when allowing for mode shift. It is not explicitly a mechanism for increasing mode speed as demand increases, particularly as the objective of modal shift (in the sustainable transport field) is to move to slower modes.

3. Methodology

In this section, we first briefly describe the general modelling platform used for our analysis. We then describe how modal shift options are implemented in the model, for urban passenger travel demand. The underlying data assumptions which underpin this implementation are then presented, including urban transport demands, modal shift potential, time budgets and infrastructure costs.

3.1 ESME overview

ESME (Energy Systems Modelling Environment), developed by the Energy Technologies Institute (ETI), is a fully integrated energy systems model (ESM), used to inform the ETI's technology strategy about the types and levels of investment to make in low carbon technologies, to help achieve the UK's long term carbon reduction targets (Heaton 2014). Built in the AIMMS environment, the model uses linear programming to assess cost-optimal technology portfolios. The mathematical programme is similar to that used in other bottom-up, optimisation models, such as MARKAL-TIMES (Loulou et al. 2005), where the objective function is to maximise total economic surplus, subject to predefined

technology capacity and activity constraints, as well as policy constraints (e.g. Renewable Energy target). The total economic surplus is calculated as the sum of the discounted system wide costs, including the change in consumer surplus and costs associated with technology investment and operation, and resource commodities.

Transport projected demands are exogenous inputs to the model, and provided for individual modes, based on forecasts from government analysis, including the National Transport Model (DfT 2012). Regional projections are further estimated, based on a range of regional datasets, including population statistics. In ESME, each mode demand is separately satisfied in a given period, net of any price-induced demand response.

3.2 *Model implementation of modal shift*

Endogenising a shift between transport modes is a significant challenge in bottom-up optimisation models (as discussed in the earlier section of this paper). Daly et al. (2014) first introduced an approach to achieve this; instead of specifying individual travel demands, a single passenger travel demand is introduced, and different modes compete to meet this demand based on their costs (technology, fuel and infrastructure) and associated travel time. The optimisation is subject to an aggregate travel time balance, and the model is allowed to invest in infrastructure which reduces the travel time associated with different modes. Hence, with a high marginal cost of CO₂, the model invests in infrastructure which enables a mode-shift away from private cars.

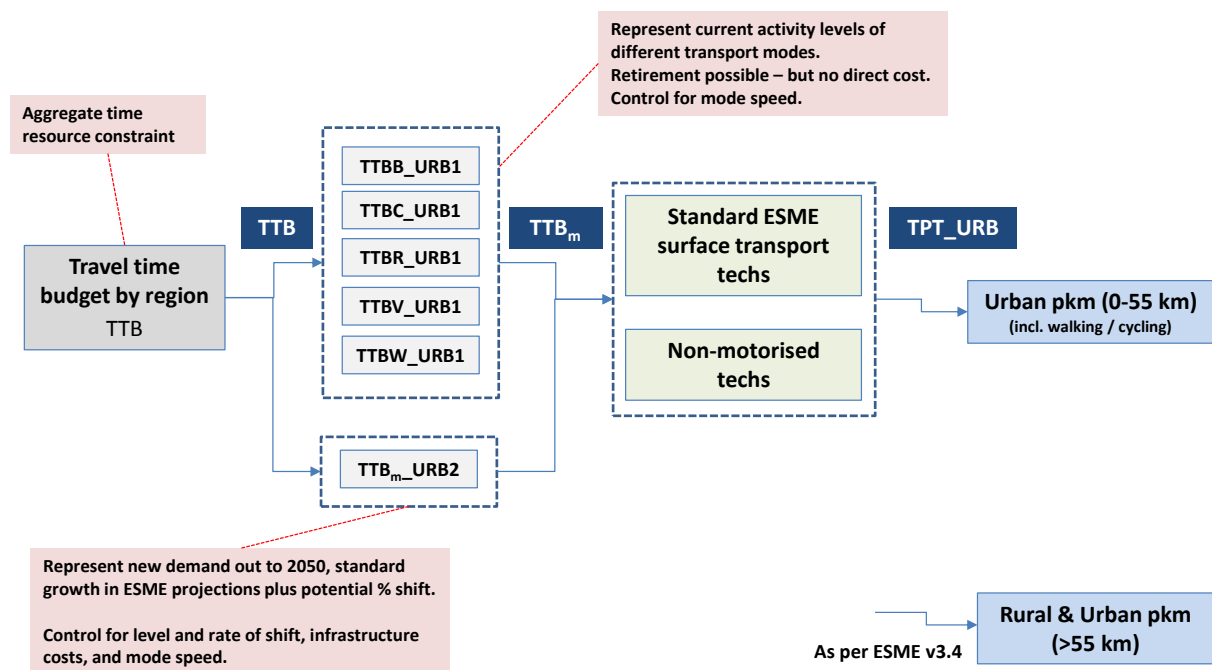
The approach in this paper builds from that developed by Daly et al. (2014). We introduce two new constraints to better represent the dynamics of mode shift: firstly, the maximum modal shift potential from cars to non-car mode, and secondly, the rate of modal shift. In addition, all existing constraints in the model for different rates of vehicle uptake are maintained.

The focus of this modal shift analysis is urban passenger travel demand for trips less than 55 km in distance. This is the travel demand for which modal shift is most applicable, given that the potential for public transport, walking and cycling is strong in dense populations and shorter trips, and is estimated via disaggregation of ESME demands using assumptions from the 2010 National Travel Survey (NTS,

DfT 2012b). This is detailed further in section 3.3. Longer distance (>55 km) urban demand and all rural surface transport demands are modelled as per the standard version of ESME, using mode-specific travel demands.

A schematic representation of the modal shift implementation in ESME (version 3.4) is provided in Figure 2. On the right-hand side, urban passenger kilometres (TPT_URB) can be met by any given mode subject to a set of constraints. However, all modes now require an input TTB_m ,⁷ this dummy resource represents travel time resource per kilometre. For every kilometre provided by a specific technology, time resource (travel time budget, TTB) will be consumed, which is capped based on the average per capita time budget (highlighted on the left hand side of Figure 2).

Figure 2. Implementation of modal shift in ESME



The availability of TTB_m is also controlled by TTB_m_URB1 / $URB2$ dummy technologies. TTB_m_URB1 technologies represent current activity levels of modes, and therefore have zero costs in the model. In theory, they can be retired if modal shift resulted in reductions below the base year activity level of a given mode. TTB_m_URB2 technologies need to be invested in if current activity levels of a mode increase above base year levels, as they represent new capacity, and associated infrastructure

⁷ Specifically, TTBB (for buses), TTBC (for cars), TTBR (for rail), TTBV (for cycles) and TTBW (for walking).

costs. (This of course assumes cost additions even if current infrastructure utilisation is not at 100%). These technologies also control for the maximum growth of a given mode and the rate of growth (as described in section 3.4).

3.3 Urban passenger transport projections

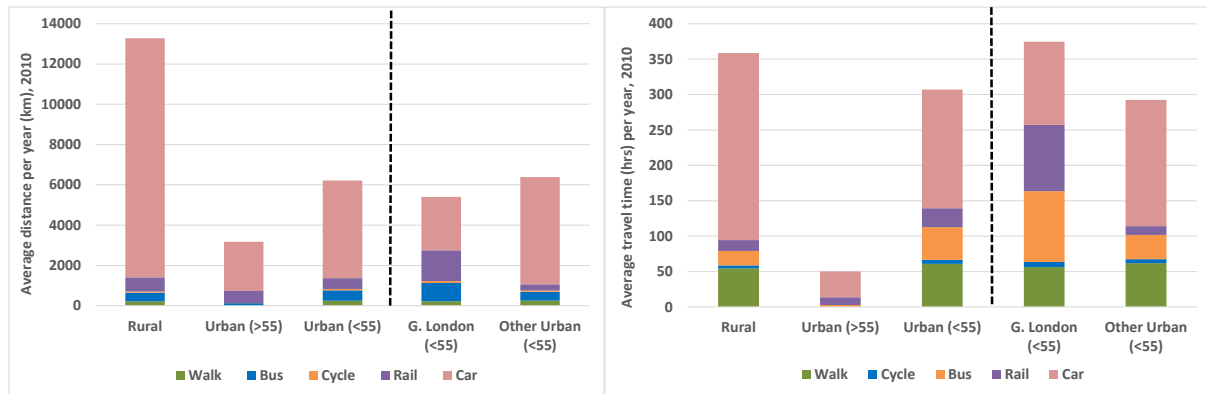
Allowing for competition between urban modes means the use of a single non-mode-specific travel demand, expressed as passenger-km. The demand projection has been estimated primarily using NTS data; from the 2010 dataset, per capita travel demand by mode has been determined for two trip types – i) urban household trips of <55 km, and ii) urban household trips of >55 km & all rural household trips

Due to significant differences in trip profile, London households have been differentiated from all other regions. Per capita mileage values are shown in Figure 3, as is the travel time per capita, an important metric in determining travel time budgets and mode speed (as discussed later). Per capita mileage is dominated by car travel, accounting for 87% of ‘Urban >55km & rural’ and 78% of ‘Urban <55 km’. For Greater London, the car share for ‘Urban <55 km’ is much lower, at 49%.

These per capita values have been scaled, using population estimates from the Rural/Urban Local Authority Classification (Defra 2008),⁸ to determine total mileage by region by mode. The resulting % shares by mode between ‘urban <55 km’ and ‘urban >55 km & rural’ travel demands is then applied to the ESME travel demands. Walking and cycling demands, not in the current version of ESME, are based on the actual scaled estimates.

⁸ Dataset of population for England LAs can be found at <http://archive.defra.gov.uk/evidence/statistics/rural/documents/rural-defn/LAClassification-dataset-post0409.xls>.

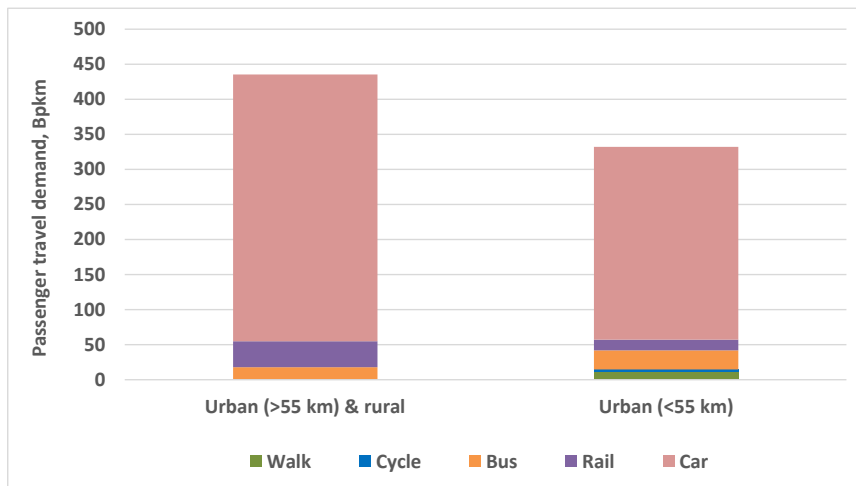
Figure 3. Per capita rural and urban mileage (left) and trips (right) by mode, NTS 2010



A final step is to aggregate the ‘urban <55 km’ demands by mode into a single urban demand (labelled TPT_URB in the model). The ‘urban >55 km & rural’ travel demands are included in the model as mode-based demands, and not subject to modal shift. The resulting ‘urban <55 km’ demand is approximately 42% of total surface transport passenger demand (see Figure 4).

The demands are projected based on the ESME demand projections. For the purpose of simplicity, it is assumed that the relative split between urban and rural demands remains the same over time. For walking and cycling, provided only for the ‘urban <55 km’ demand, these are projected based on estimates of future population.

Figure 4. Surface transport passenger demands, 2010



3.4 Modal shift potential

There are three sets of assumptions that impact on modal shift in the model, including -

- Maximum level and rate of modal shift

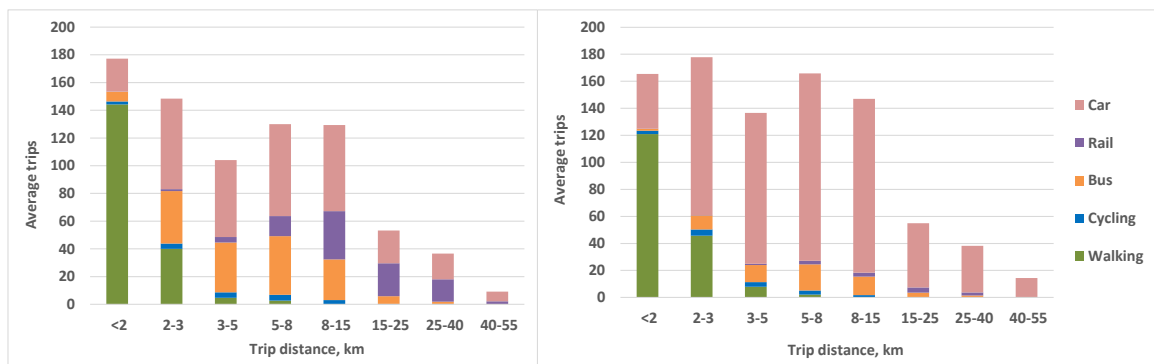
- Speed of modes, given the population’s time budget requirement
- Costs of different modes

In this section, we explore each in turn, describing the assumptions used in the modelling.

Maximum level and rate of modal shift

Determining rates of possible future modal shift is a challenge, for the range of reasons described earlier. Our starting place is to first consider the maximum share that any single mode can take from that currently met by cars, based on the current trip distance profiles, and assuming these remain static in future years. Based on the NTS 2010, the trip profile by distance for London and for the average urban region (excl. London) is shown in Figure 5. As an example, it is evident that the walking mode can only meet very short distance trips – and therefore its potential capture of car demand share (in distance terms) is limited.

Figure 5. 2010 trip distance profiles for Greater London (left) and other urban regions (right)



While the above analysis provides some limit to modal shift, further consideration needs to be given to the limits of mode shift within the bounds already provided. Therefore, an additional step taken was to set the maximum per capita demand by mode that could be achieved by 2050. Limits are shown in Table 1; they are informed by other analyses and international experience in some instances but remain an important assumption for sensitivity analysis due to the wide range of assumptions that could be adopted. Broadly speaking, per capita demand levels tend to be higher in London by 2050, due to higher existing levels and a more extensive public transport infrastructure. While Table 1 shows increases across modes, for cars it reflects the illustrative shift away based on maximum per capita levels being met across all other modes.

Cycling limits have been considered in most detail (due to data availability). By 2050, per capita levels increase by 700%; this is in line with the Mayor’s current ambition, to increase cycling trips by 400% by 2026,⁹ and is also reflective of other analysis of cycling potential in London (TfL 2010). Per capita km increases from 89km to 670km by 2050, still below the current Dutch average of 850km per year.¹⁰ A strong average increase, albeit lower than for London, is assumed for other regions, to 400km per capita by 2050. Further research is needed to enhance our understanding of the share that bus and rail travel could capture by 2050.

Table 1. Maximum levels of per capita demand by mode in 2050

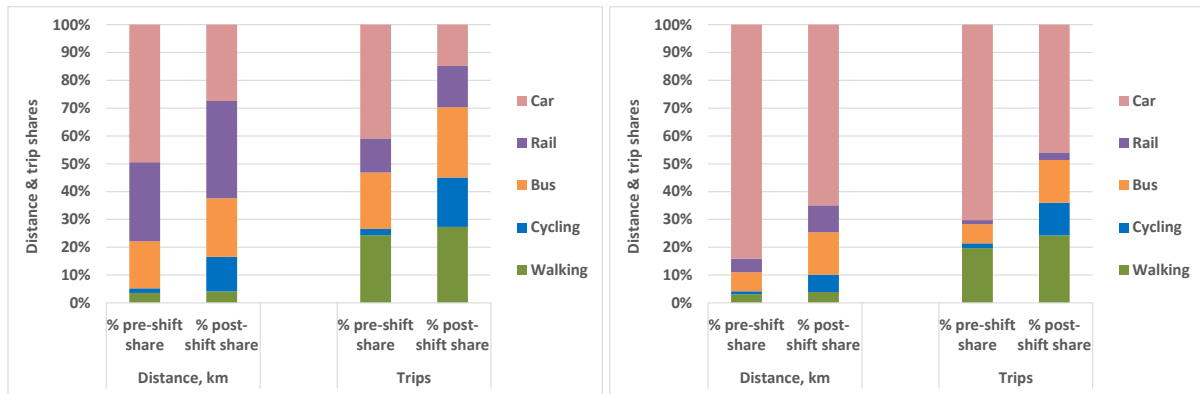
Mode	Greater London		Urban (exc. London)	
	Max % increase in trips by 2050	Max per cap. km demand (current level)	Max % increase in trips by 2050	Max per cap. km demand (current level)
Cycling	700%	670 (89)	580%	400 (66)
Bus	25%	1130 (906)	125%	964 (430)
Rail	23%	1875 (1526)	91%	616 (313)
Walking	12%	220 (192)	25%	246 (199)
Car	-64%	1470 (2649); -44% in km travelled	-34%	4106 (5318); -23% in km travelled

The maximum shares of the different modes by mileage and trip for Greater London and the other urban regions is shown in Figure 6. The pre-shift shares are illustrative of the situation today while the post-shift shares reflect all non-car modes at their maximum potential (on a per capita basis), with any increase reducing the share of the car mode.

⁹ London’s cycling revolution, see <https://www.london.gov.uk/priorities/transport/cycling-revolution>

¹⁰ Ministerie van Verkeer en Waterstaat report, *Cycling in the Netherlands*, <http://www.fietsberaad.nl/library/repository/bestanden/CyclingintheNetherlands2009.pdf>

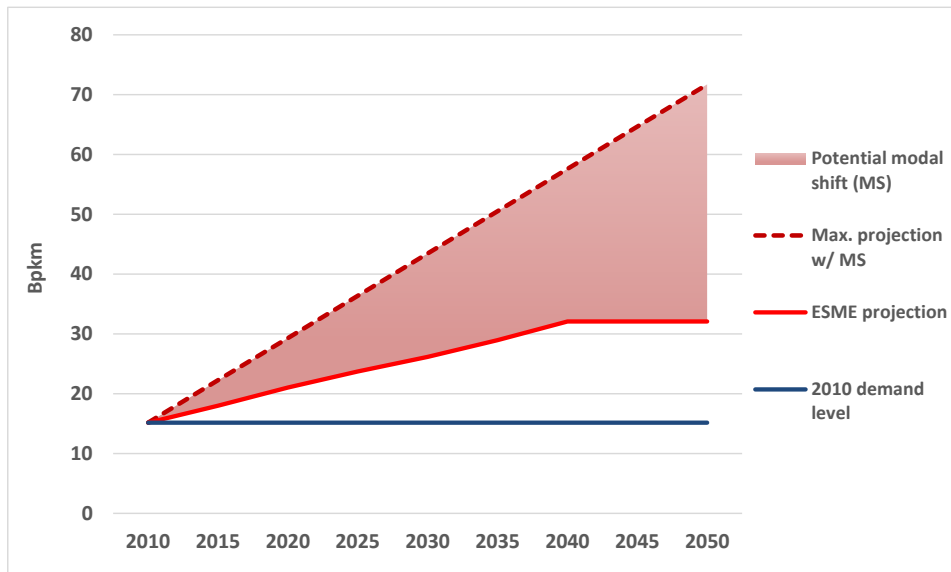
Figure 6. Illustrative per capita km / trip shares pre & maximum post shift for Greater London (left) and other urban regions (right)



Having included a maximum potential shift, we also need to consider the rate at which this shift can take place. For simplicity, the increase in modal shift has been linearly interpolated between the current and maximum level in 2050. The implementation approach can be further elaborated using the example of rail provided in Figure 7.

The current level of rail demand in 2010 is around 15 bpkm per year; demand projections used in ESME suggest this could rise to just over 30 bpkm by 2050, shown by the red trend line. The potential additional growth due to modal shift is shown by the shaded area. Any growth in demand above the 2010 demand level is subject to additional infrastructure costs, and controlled in the model implementation by the TTB_m_URB2 technologies (see Figure 2). Such an approach is taken for all non-car modes. For car modes, only the ESME projected level is permitted, with no potential for additional growth via modal shift.

Figure 7. Rate of modal shift for rail



Two points are worth highlighting; firstly, all modes can potentially compete with each other for travel demand; for example, non-car modes can displace cars but also other non-car modes. Cars are treated differently, in that they cannot displace other modes i.e. car demand cannot increase above the projected level in the standard ESME projection). Secondly, it is likely that most modes will at least retain their 2010 capacity levels, as this is existing infrastructure, with no additional costs incurred. However, depending on the stringency of other constraints e.g. CO₂ or time budgets, it is possible for the model to displace a given mode below its 2010 level.

Mode speed and time budgets

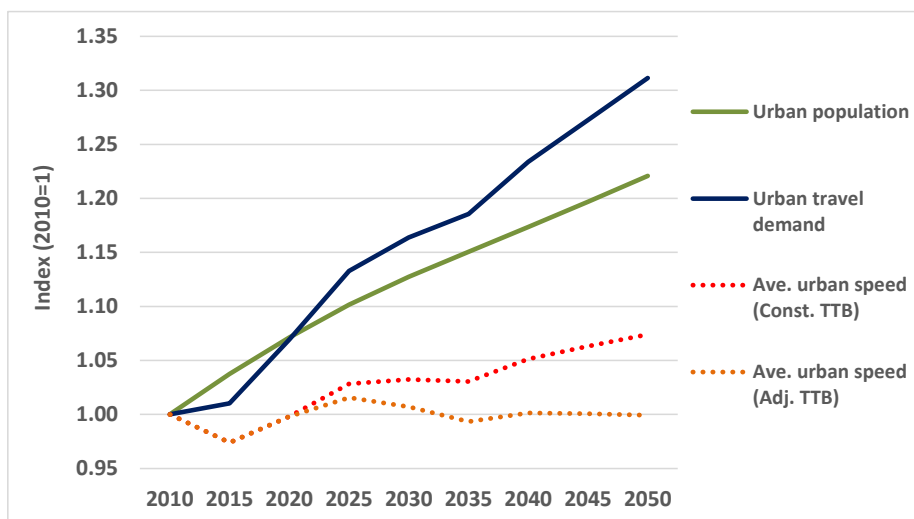
The concept of time budgets (described earlier) is included in the model as an aggregate time resource, TTB. Each mode has a given average speed, and therefore requires different levels of time resource per pkm delivered. The ratio of time resource per pkm delivered is controlled by proxy technologies in the model (URB1 and URB2). They consume TTB, and produce TTB_m, which goes to the relevant transport technologies depending on their mode. The function of this constraint is that it ensures a balance of modes; slower modes could not take over entirely as the aggregate time budget requires faster modes to be part of the mix.

The travel time budget for a region can be expressed as

$$TTB_{i,b} = POPN_{i,b} \times TTB \times AF_b$$

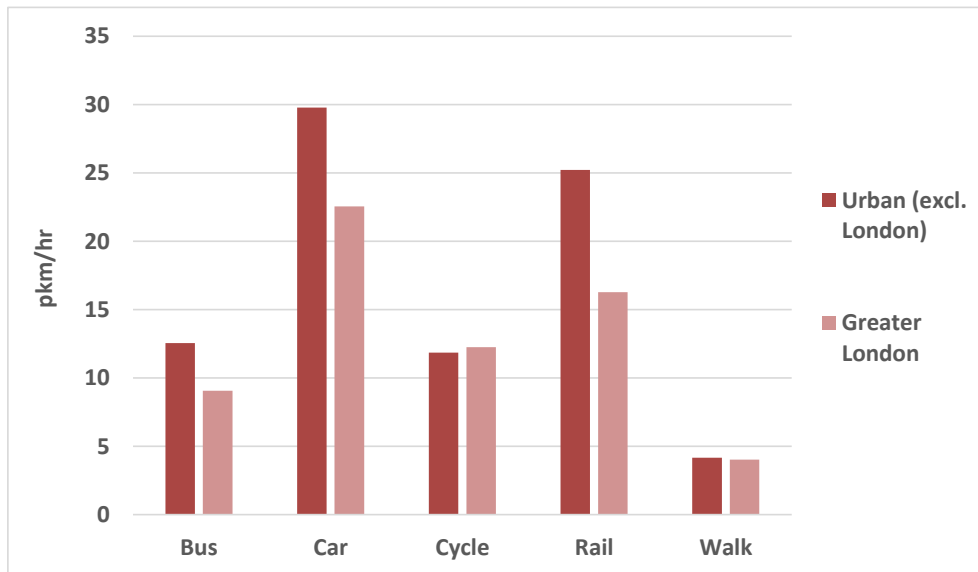
where for a given year b , POPN is the regional urban population, TTB is the per capita time budget and AF is an adjustment factor to allow for a slower mix of modes in the future. Index i denotes the region. AF is an important assumption, as illustrated by Figure 8. If we plot population (pink line) and urban travel demand (blue line) over time, stronger growth in travel demand is apparent, due to an assumed growth in per capita demand, particularly for cars (although this continued growth is contested by some; see Metz (2010) for the arguments). If we assume a constant TTB (based on the current average) over time, average urban speeds will have to increase (red discontinuous line).

Figure 8. Projected population and assumed average speed based on constant and adjusted time budgets



When thinking about modal shift, and its role in reducing emissions, we are considering the prospects for slower modes. A comparison of mode speeds used in the modelling, based on NTS 2010 data, is shown in Figure 9. As Bannister (2008) states *there is a contradiction between the desire to speed up and the desire to slow traffic down*. To this end, we have assumed that greater demand for slower modes implies a reduction in overall travel speeds, increasing per capita travel budgets by 7.5% by 2050. This is equivalent to a 61 minutes per day budget compared to 57 minutes, the current level. Given uncertainties in per capita travel demand increases and travel budgets in future years, this is small adjustment, and one that requires further sensitivity analysis.

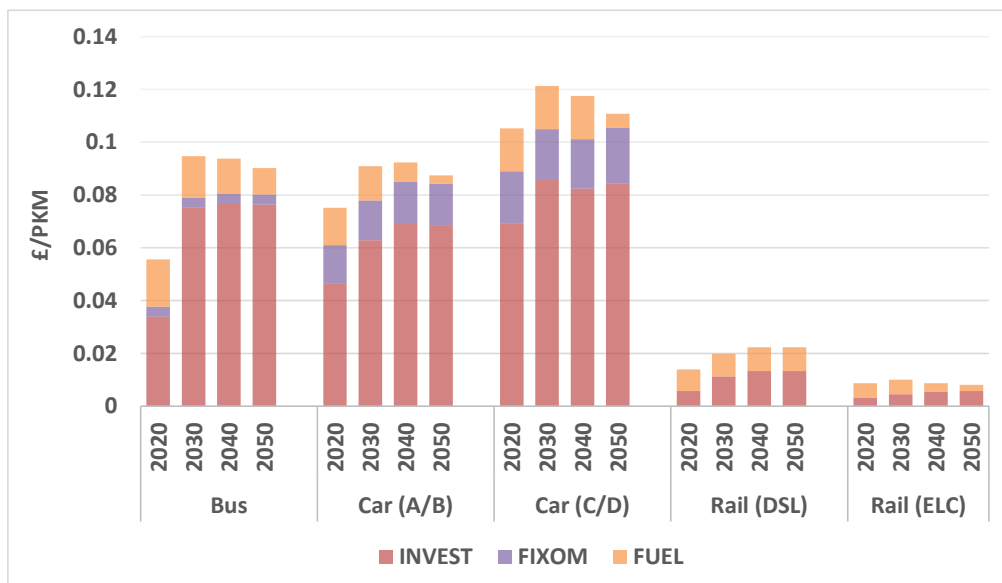
Figure 9. Average mode speeds used in modelling, based on NTS 2010



Mode costs

Within the mode shift, time budget and other transport sector constraints, the mode choice decision is a function of cost-optimisation. The current cost differences in mode (based on a standard low carbon ESME run) are shown in Figure 10. These differences are not critical in the standard version as modal competition is not a feature.

Figure 10. Average costs by mode based on low-carbon deterministic ESME run



If we are to allow cost optimisation in the modal shift version, a more comparable set of costs is required. This has been done by adding infrastructure costs to each of the modes. This is particularly

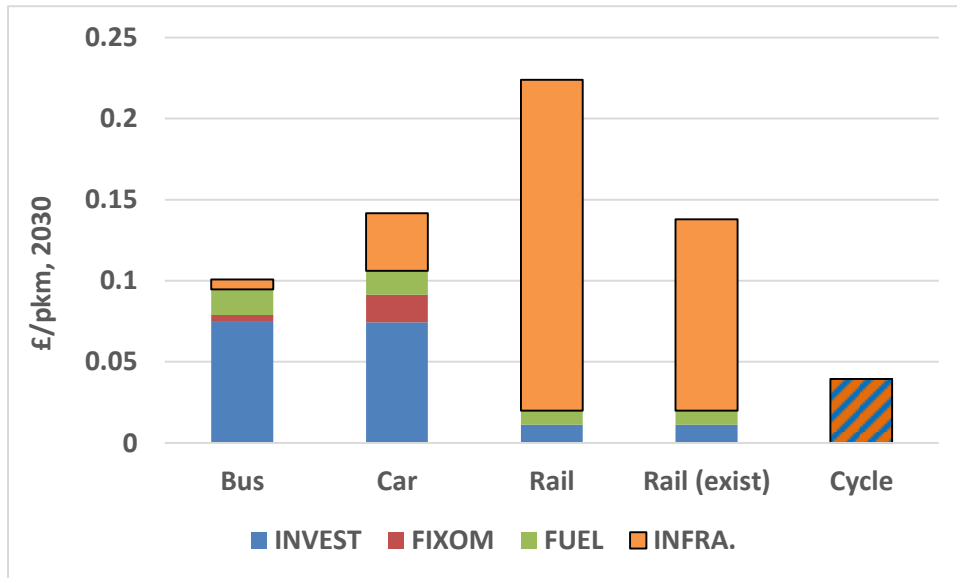
critical for the rail mode, which only capture investments associated with rolling stock, but not the rail system as a whole.

Table 2. Infrastructure cost assumptions by mode

Mode	Sources of information for infrastructure costs
Cycling	The costs for cycling represent the year-on-year investment required to get to a specific level of cycling trips, and therefore captures a broader set of measures than simply investment in infrastructure. In the <i>Get Britain Cycling</i> report, it was stated that there was a consensus that around £10-20 / capita year-on-year spend being able to deliver trip mode shares of 20-40% (Goodwin 2013); The London cycling strategy is funded at £18 / capita to deliver a 400% increase in cycling activity by 2026 (GLA 2013). These values have been converted to £/pkm by calculating the total investment needed to deliver a 20% or 40% mode share. A 20% mode share costs more (on a pkm basis) due to the lower pkm delivered, if we assume a constant £20 per capita year-on-year spend. This decreases as a higher share is achieved. The costs are entered into the model as decreasing over time, assuming that the cycle mode share is increasing. The investment cost of bikes has not been explicitly included.
Bus	As per car mode (below); the pkm costs are lower due to the higher passenger occupancy of buses (McKinsey estimates are in vkm, not pkm).
Rail	For rail, the costs of infrastructure investment and system operation have been added, based on the DfT (2011) report <i>Realising the potential of GB rail: final independent report of the rail value for money study</i> . Projected future investment needs are informed based on McKinsey (2011) <i>Keeping Britain moving: the United Kingdom's transport infrastructure needs</i> .
Walking	No additional costs are assumed.
Car	Future investment needs are estimated based on McKinsey (2011) <i>Keeping Britain moving: the United Kingdom's transport infrastructure needs</i> . A cost per pkm estimate can be calculated based on the investment needed (£181 cumulative to 2030) for a 28% increase in road demand.

Based on the above sources, the following infrastructure costs were added to each of the modes. These are the costs in 2030; assuming the cycling share increases in post-2030, the associated cost would be lower. Infrastructure costs are lower for existing rail, as they only include system operation, not the capital costs of new infrastructure. The key changes (relative to Figure 10) include rail being much more costly, particularly new rail. Cycling is by far the most cost competitive (for those trips that can be undertaken by cycling) while bus emerges as the most cost-effective motorised mode.

Figure 11. Average costs by mode, including infrastructure costs



* Cycle costs represent those necessary to increase cycling activity, and include infrastructure and investment.

While adding infrastructure costs ensures a more comprehensive representation of technical costs, it is important to note that the modelling framework could consider a range of other costs, although their use in the analysis would need to be carefully thought through. The first are externalities associated with mode safety, health impacts associated with active transport, and environmental impacts (noise and air pollution). The second are those that reflect behavioural decisions around transport utility, such as value of time and / or convenience / reliability.

4. Draft results

4.1 Model sensitivities

The analysis undertaken focuses on the operation of the model using this modal shift approach, based on a range of sensitivities. These sensitivities highlight the impact of different constraints on the model solution, and the role of modal shift. The different constraints or assumptions being tested are those in the table column headers. All model runs are deterministic, and use ESME v3.4.

Table 3. Model runs for modal shift analysis

Model run	Description, incl. purpose of sensitivity	Time budget?	CO2 cap?	Mode shift level?	Additional car mode costs?
Ref	ESME v3.4 standard run for comparison	No	Yes	No	No
MS-Ref	Central shift case (as presented)	Yes	Yes	Central	No
MS-No Cap	No CO2 cap case	Yes	No	Central	No
MS-High	High shift case	Yes	Yes	High	No
MS-HighCC	High car costs (+£0.1/pkm) case	Yes	Yes	Central	Yes
MS-NoTTB	No time budget case	No	Yes	Central	No
MS-HighCC NoTTB	Max shift case: high car costs (+£0.1/pkm) & no time budget constraint case	No	Yes	Central	Yes

4.2 Levels of modal shift

Figure 12 is the key graphic from this analysis, and shows the change in demand across modes relative to the case where no mode shift is permitted (Ref). To provide some context, a change of 20 bpkm in 2030 is 5.2% of all shorter distance (<55 km) urban surface passenger demand; in 2050 its share is 4.6%. However, in terms of the additional demand growth relative to 2010 levels (increase in bpkm relative to the 2010 level), 20 bpkm represents a much larger share, at 37% in 2030 and 19% in 2050.

As the rate of shift constraint is relaxed over time, modal shift increases across all sensitivities. Post-2020, cycling increases at the expense of rail in all sensitivities except where the time budget constraint is removed, and car travel is penalised (MS-HighCCNoTTB, MS-NoTTB). This is not surprising, given that these are the lowest and highest cost modes respectively. The time budget constraint does moderate their uptake, given their average mode speed and the percentage share of trips that cycling is applicable for. This result should not be viewed, however, as cycling replacing rail travel (although this could be foreseen in some urban areas such as London); it is rather a re-adjustment of the range of trip distances covered by different modes.

Notably, the carbon constraint does not have a discernible impact on the role of mode shift (MS-NoCap); when removed, mode shift remains at similar levels to MS-Ref. This implies that mode shift is also important for reducing costs, not only as a mitigation option under a carbon constraint. Larger

shifts are observed, and across different modes, when either car travel is penalised with higher costs and / or travel time budgets are removed.

Removing the travel time budget results in a reduction in car and increase in bus travel (MS-NoTTB). The cycle share does not increase further due to limits on its share of overall travel demand. By 2050, this leads to a shift of 40 bpkm (or 9% of total demand, 38% of demand growth relative to 2010). Compared to MS-Ref, removing the time budget constraint allows for double the modal shift. Penalising car travel results in a three-fold increase in the MS-Ref levels, under MS-HighCCNoTTB. In addition to a growth in bus and cycling modes, rail now become cost-competitive, and is now a mode that grows rather than declines (relative to Ref).

The analysis suggests two key insights: Firstly, a shift away from car travel will require a move to slower modes, requiring time budgets to increase. In the MS-NoTTB case, this translates to a 14% increase in 2050, compared to 2020 levels (66 vs. 58 min./day/capita). Secondly, reducing the car share requires significant increases in car travel costs relative to other modes.

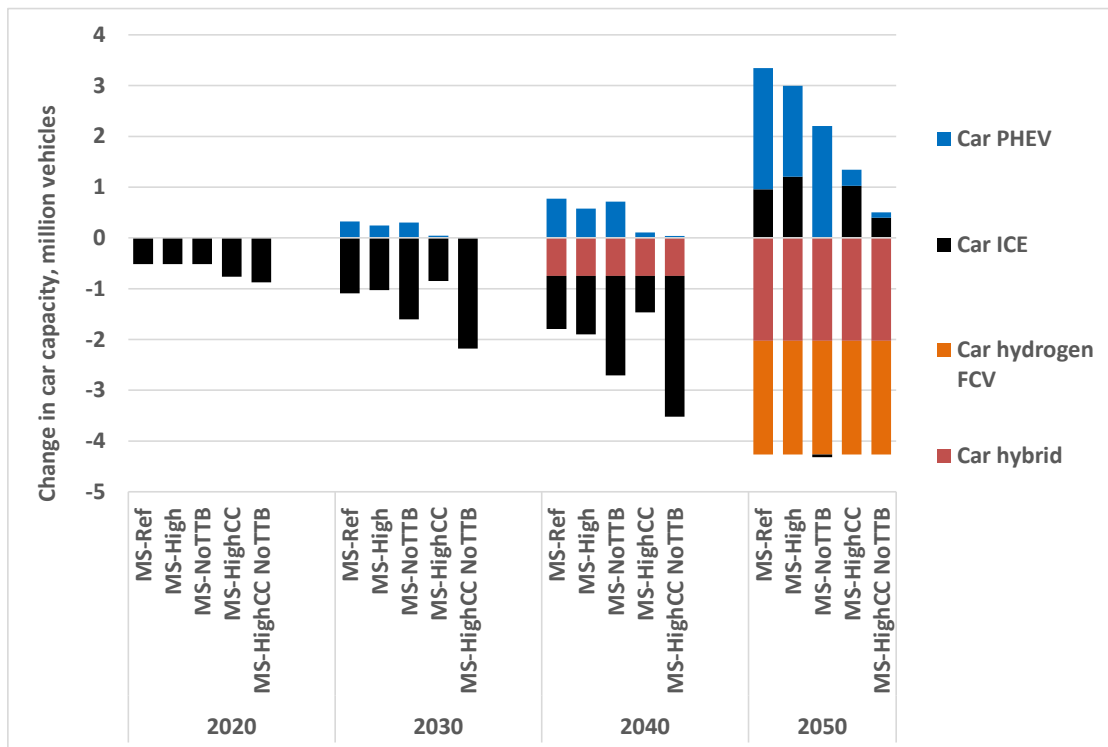
Figure 12. Change in mode due to modal shift option, 2020-2050



4.3 Impacts on transport and wider system technology mix

At the technology level, it is interesting to explore the impact of modal shift on the technology mix, both in the transport sector and the wider system. The change in the car stock is shown in Figure 13 (comparing modal shift sensitivities to Ref case), and highlights the shift away from ICEs in the periods 2020-2040, and then quite a significant change in the last period, with a shift away from hydrogen to PHEVs. (For context, 4 million cars in 2050 is just under 10% of the total car fleet).

Figure 13. Change in car stock capacity levels by type, 2020-2050



A reduction in overall car stock is expected, where the modal share of cars reduces. The reasons for changes in technology mix, particularly in 2050 is not so obvious. While our conclusion above was that modal shift levels were not largely impacted by the carbon constraint, at the technology level some changes are observed. As car usage reduces, the more carbon intensive vehicles are reduced (ICE / hybrids). The situation in 2050 is somewhat different where hydrogen vehicles reduce, allowing for slightly more ICEs. In this period, modal shift appears to be creating ‘headroom’ for higher emission vehicles, and reducing the level of high cost alternative vehicles.

This trade-off between sector emissions and mitigation costs results in lower emission reductions in this periods from the transport sector, as shown in Figure 14. This compares to increasing percentage

emission reductions pre-2050, from 2-3% in 2020 to 6-9% in 2040. However, in 2050, the reductions are in the 3-4% reduction range. The reduction in the deployment of hydrogen vehicles (in addition to changes elsewhere in the system) leads to a CO₂ shadow price of £818/tCO₂ (undiscounted) in MS-Ref compared to £1044 in the standard ESME Ref case.

Figure 14. Change in CO₂ emissions, 2020-2050

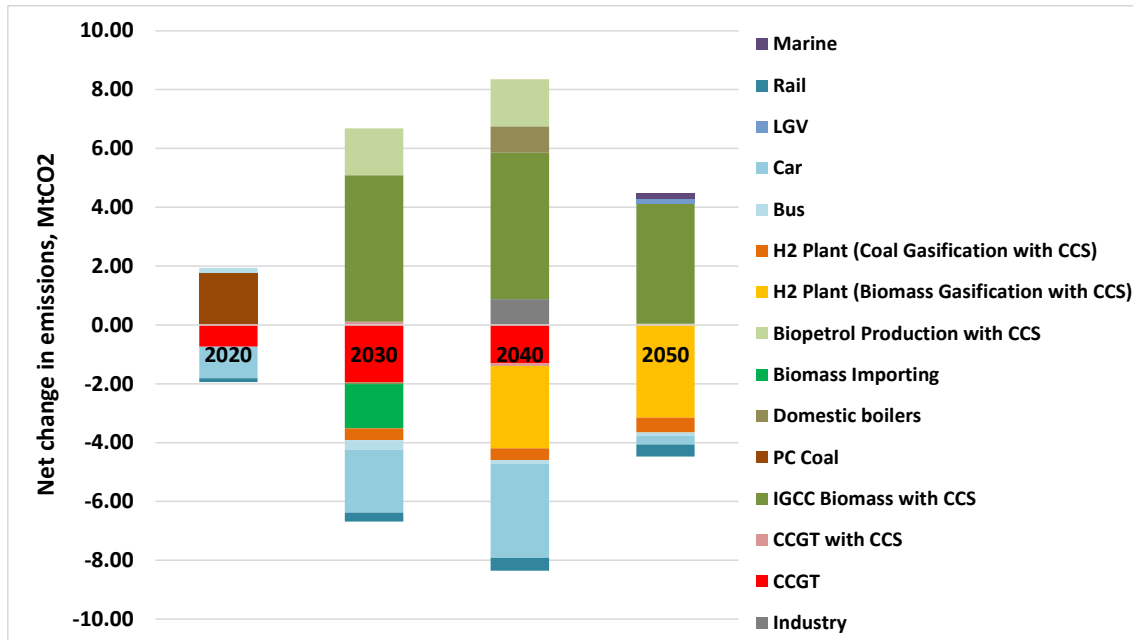


The broader impact on emissions across the energy system is shown in Figure 15. The shift in the type of emission source increases to 2040, and then reduces in 2050, following the pattern observed in emission reductions for passenger surface transport. The reductions in emissions from transport are shaded blue. The main shift is a reduction in more expensive mitigation technologies such as IGCC biomass with CCS, and biopetrol production with CCS (shown by the green shaded column segments). There is also some reduction in the CCGT generation to 2040.

Interestingly, an increase in emission reductions from hydrogen production in 2040/2050 indicates an increase in hydrogen use (~13% increase), despite a reduction in car hydrogen FCV uptake in 2050. The increase use is in the generation sector, which sees an increase in consumption of over 20% in 2050. This increased use of hydrogen generation replaces the other generation technologies (CCGT, IGCC biomass w/CCS).

While the emission changes shown below are relatively small (at the system level), the comparison is being made with MS-Ref, the least ambitious modal shift case. System changes are much larger under those sensitivities with no time budget and high car costs.

Figure 15. Change in CO₂ emissions by source (MS-Ref compared to Ref), 2010-2050



5. Discussion and conclusions

In this paper, an approach to modal shift, building on that proposed by Daly et al. (2014) has been described. It shows that such an approach, albeit modified, can be applied to a large systems model and produce insightful results. In addition, it makes some progress in characterising infrastructure and associated costs more explicitly, and incorporating non-motorised modes.

The results show that transport sector behavioural measures can have an important impact on system costs and emissions. Results are clearly driven by some important constraints and assumptions that in turn point to a number of insights. Critical is the TTB; small changes in the per capita budget allow for significantly higher levels of modal shift. This means that in addition to many others, there is a particular trade-off between moving towards a more sustainable transport and the speed of travel. A key question for policy is whether this is acceptable to consumers? For example, how much road space should be re-allocated to cycle lanes? There is then a follow-up question as to whether this type of analysis should

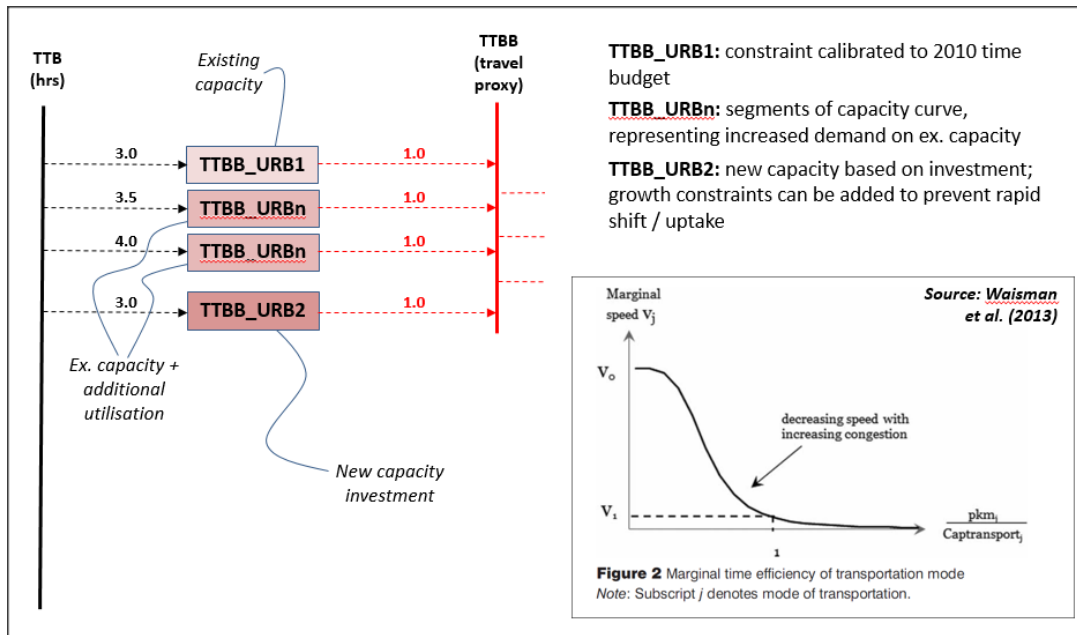
be considered the value of time, as is standard in transport policy appraisal to better capture this trade-off.

The other important factor identified is that reducing car travel can be done through imposing significant additional costs. Finding the threshold cost at which a large difference is observed is required via additional sensitivity analysis (and could be done via ESME's Monte Carlo framework). Such costs imposed make other modes, notably rail in this analysis, much more attractive economically.

Of course, there are evident limitations with this kind of analysis. It optimises a set of techno-economic costs (incl. infrastructure) within a set of constraints. What it does not do is take account, in economic terms, of the many other factors that feed into mode choice. There is therefore still a discussion to be had as to whether the optimisation outputs of the model can produce robust findings; at the minimum, however, the model framework can be used as a useful exploratory framework for assessing the impact of different levels of mode shift on the transport sector and wider system.

A number of avenues could be explored for further research. This includes the relationship between capacity utilisation in the model versus speed. Figure 16 illustrates, based on the concept in Waisman et al. (2013), that the existing capacity (TTBB_URB1) could be disaggregated to represent reduced speeds as capacity is used (TTBB_URBn). The model would need to choose between maintaining existing capacity (at lower speeds) or investing in new capacity (TTBB_URB2).

Figure 16. Introducing capacity constraint into mode shift model



Another area for further research is in expanding the representation of the costs and benefits of modal shift. This could include costs associated with slower speeds (through a value of time input) and benefits associated with lower external costs (air pollution reductions, other active transport benefits). Such factors are potentially crucial for non-motorised modes. A third factor is to further explore the benefit of including a walking mode; whilst it is included in the model, it has not been sufficiently characterised – and has limited impact. Again, at the minimum, its inclusion allows for scenario analysis about the role of non-motorised modes in a future energy system. Finally, a key benefit of urban mode shift is not represented in this modelling but should be considered further. While the bpkm displaced is modest, mode shift displaces a much larger share of trips taken. This could have strong positive benefits for reducing congestion during peak times of the day, across different urban locations.

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