Modelling Transport Modal Choice and Its Impacts on Climate Mitigation

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Abstract

Transport accounts for 23% of energy-related CO₂ emissions globally and transport CO₂ emissions are projected to double by 2050. Climate change mitigation clearly requires a focus on transport that should include improved representation of travel behavior change in addition to increased vehicle efficiency and low-carbon fuels. Most available energy/economy/environment modelling tools focus however on technology and fuel switching and tend to poorly incorporate travel behavior. This paper addresses this gap by focusing on a key element of travel behavior, namely modal shifting. We introduce a novel approach to modelling modal choice in TIMES, a bottom-up, technology rich, least cost energy systems model. In typical TIMES models, individual modal travel demand is exogenously defined over the model time horizon and while technologies can compete within modes on the basis of cost (fuel costs, investment costs and O&M costs), there is no competition between modes. Here, we build a simple illustrative TIMES model, in which future overall travel demand is exogenously defined but not specified by individual mode. We allow competition between modes and impose a constraint on overall travel time in the system. This constraint represents the empirically observed travel time budget (TTB) of individuals and enables competition based on time as well as on cost, ensuring that faster and more expensive modes can compete. We further introduce a new variable, called travel time investment (TTI), which acts as a proxy for infrastructure investments (for example, new bus services or rail lines) to reduce the time associated with travel. We populate the model with data from California, US and generate results to 2020 for a reference scenario, an investments scenario and a CO₂ emissions reduction scenario. The results show the significance of modal shifting in the CO₂ mitigation scenario.

Keywords: Energy systems modelling, modal choice, transport, climate mitigation

1 Introduction

1.1 Background

Transportation contributes to 23% of energy-related CO₂ emissions globally. With increasing demands especially for light-duty vehicles, freight, and aviation, global
transport CO₂ emissions are expected to double by 2050 (IEA 2011). Reducing greenhouse gas emissions from the transport sector will require complementary policies in improving the efficiency of vehicles, introducing low-carbon fuels and advanced vehicles technologies, and better travel demand management (Schäfer, Heywood et al. 2009; Skinner, Essen et al. 2010). Most of the growth in demand for cars will come from developing countries, as car travel in developed countries essentially saturated, and is projected to remain flat in the next few decades (IEA 2010). On the other hand, public transit and aviation already play an important role in many developed (especially Europe) and developing countries (Figure 1). The importance of their role is expected to continue to increase given the need to drastically reduce on-road transportation emissions in order to meet stringent climate targets (Figure 1) (Fulton, Cazzol et al. 2009; IEA 2010).

![Figure 1: Relative share of transport modes in the three metaregions and the world, in history (1950 and 2005) and in projections (2050) based on various scenarios. SRES-B1: Special Report on Emissions Scenarios – SRES, rapid economic growth and advanced technology scenario. EPPA-RR: MIT Emissions Prediction and Policy Analysis (EPPA) CGE model. Source: (Schäfer, Heywood et al. 2009).](image)

However, while most of the integrated assessment (IA) models that governments rely on for developing climate mitigation policies have been able to project portfolios of advanced fuels and vehicle technologies given climate goals, most of these models are ill suited to examine potential travel demand changes and travel mode shifts given climate policies and changes in fuel prices, and most importantly the necessary
investments needed to reduce vehicle travel, increase public transit shares, and non-vehicle infrastructure given climate goals (Schäfer 2012). Most IA models use scenario describing future travel mode shifts without explicitly linking demand changes to drivers (e.g. fuel price changes) or infrastructure and technology investment decisions. This is evident in Figure 1 and other studies (Fulton, Cazzol et al. 2009; IEA 2010; Skinner, Essen et al. 2010).

A recent seminal paper by Schäfer (2012) provides a critical review of the (lack of) modelling of behavioral changes in transportation in energy/economy/environment (3E) models, compares common methodologies employed in IA models, their shortcomings and gives recommendations for future improvement. This paper states that “Overall, introducing behavioral change in transportation into E3 models is feasible and intellectually rewarding. However, when pursuing holistic approaches to mitigating energy use and emissions, it is indispensable.” Our paper explores some of the recommended methodologies and applies them for the first time in a bottom-up optimization modeling framework using the TIMES model and implements this in a case study based on the Californian TIMES model.

We will describe the TIMES modeling framework and review the role of transport in energy models and key underlying concepts of travel behaviors in Section 1.2, describe our methodology in Section 2, compare results of the case study in Section 3 and conclude in Section 4.

1.2 Transport in energy systems models
Transport modelling is a very well established discipline used widely by decision-makers for planning infrastructure such as airports, roads and railways, for cost-benefit analyses, and environmental impact assessments. Transport planning models typically simulate travel trips by origin and destination, trip purpose, mode of travel and household demographics. Mode choice computes the proportion of trips between each origin and destination is often modelled using by a logit type model (de Dios Ortúzar and Willumsen 2001). Behaviour is generally a strong element of these models, whereas there is generally very little or no treatment of energy demand.

On the other hand, Energy/Environment/Economy (E3) models explicitly look at the energy system to examine issues ranging from macroeconomic interactions to looking at pathways to meeting climate mitigation scenarios. Schäfer (2012) describes how
transport is represented in a range of these models, in particular examining the role of
behaviour in transport, which is necessarily more constrained in energy models.

The TIMES model, used to implement the approach described here, is a bottom-up
energy systems model developed by the Energy Technology Systems Analysis
Programme (ETSAP), an IEA Implementing Agreement (Gallachóir et. al. 2011).
Energy systems models like TIMES are generally partial equilibrium linear
optimisation models, with very rich technological detail of the entire energy system,
from fuel production and imports to energy conversion and demand technologies. The
total system cost is minimised over a time horizon subject to user-defined constraints,
such as maximum system-wide CO\textsubscript{2} emissions. Demands are generally exogenously
projected, and can be derived from other models. A facility for elastic demand is
available in TIMES, where end-use can be a function of price or income. Schäfer
(2012) gives a number of examples of such models, none of which consider
behaviour. Because technology selection in these models is determined by the least
system cost, and travel behaviour is largely dictated by user costs, which can include
time costs and barrier costs, it has been difficult to model realistic modal choice
behaviour in these models. Mode choice is therefore typically exogenous, which is a
significant limitation, given that this is considered to be an important step in moving
towards sustainable mobility (Banister 2008).

Other types of E3 models include hybrid and top-down approaches, which, because
the modelling approaches are not strictly linear optimisation, typically have more
flexible and nuanced representations of travel demand, but not such a detailed
representation of energy technologies as bottom-up models. The hybrid models
include the Global Change Assessment Model (GCAM) model, developed at the
Pacific Northwest National Laboratory, which is a general equilibrium model which
solves for prices, supply and demand for all markets. Mode choice is modeled using a
logit model approach, where the cost of time is included in the generalized cost for
transport, and so increases in GDP leads to a demand for faster modes. The Canadian
Integrated Modelling System (CIMS) also includes a logit sub-model for mode and
fuel choice. A third hybrid model with transport behaviour is IMACLIM-R (IMpact
Assessment of CLIMate policies-Recursive version), developed at CIRED, which
maximizes a utility function subject to travel budget constraints. Infrastructure is
endogenous: a decrease in supply leads to congestion and lower speeds, which feeds back into the model.

Constraining overall travel time in this latter model is the essence of the contribution of this paper to modelling travel behaviour in bottom-up energy systems models. It has been empirically observed that the average daily travel time is constant across many different populations (Marchetti 1994) (Gakenheimer 1999). Figure 2 shows results from the UK National Travel Survey (NTS) on travel patterns since 1970. It shows that while total travel distance has grown by approximately 60% in the period, total annual travel time per person has stayed constant. This has introduced the concept of a fixed travel time budget (TTB), which is invariant under policy and economics. Schäfer and Victor (2000) use this TTB of 1.1 hours per day along with a fixed travel money budget to project future levels of mobility and transport mode. This paper also follows this approach, which is consistent with the linear programming approach adopted.

Figure 2: Travel time (hours per person per year), distance (miles pppy) and journeys (pppy) in the UK. Source: (Metz 2010)
2 Methodology

This section describes the basic model structure of the methodology and its implementation in a simple illustrative TIMES model. In this model, different transport modes compete on the basis of fuel and capital costs to deliver overall travel demand, while a constraint on overall travel time in the system, representing the travel time budget (TTB) of individuals, ensures that faster and more expensive modes can also compete. We introduce a new variable, travel time investment (TTI), a proxy for investments to reduce the time associated with travel. This model is then tested under a reference scenario (to 2020), an investment scenario and a CO\textsubscript{2} emissions reduction scenario.

2.1 Model structure

Motorised travel demand is represented by person miles travelled (PMT), which is the sum of demands of car (CMT), bus (BMT) and train (TMT). PMT for a technology is given by the vehicle miles travelled (VMT) multiplied by the load factor (LF, or occupancy of the vehicle). PMT is divided by long and short distance demand ($PMT_{L}$ and $PMT_{S}$) in order to capture the characteristics of the different technologies servicing the different demands: High-speed train and buses can service long distance travel, while city buses can service short distance; cars serve both. Furthermore, the speed of technologies serving long and short distance differs significantly: For example, for longer distance a rail trips, the required waiting time is absorbed by the speed of the overall journey and is more significant in shorter trips.

The model is based on a least-cost linear programming approach. It determines $PMT_{i,d}$, the travel demand for long and short distance ($d$) of each of the technologies ($i$) such that the overall system cost is minimised. The cost of technology activity, $c_{i,d}$ is the cost in $$/PMT of travel in each technology producing long or short distance travel demand $d$, given by the sum of the fuel, investment and O&M costs in dollars per PMT.

The model is constrained to meet annual short- and long-distance travel demand, which are modelled exogenously and can be based on the output of transport models, for example.
The concept of a travel time budget (TTB in million hours, mhs) is introduced to the model to represent the empirically observed fixed travel time per-capita in the real world, as described in Section 1. This enables competition between different transport modes based on travel time in addition to cost. Without this the model will be likely to switch modes immediately to the cheaper but slower and more time-costly public transit modes, which doesn’t reflect travel behaviour. Previous TIMES models in general have fixed travel demand for each mode, and while allow technologies to compete within modes, but not between modes.

Ideally, speed and infrastructure would be endogenous to the model, so that the model could invest into decreasing travel time. We introduce a variable $TTI$ (travel time investment) which is a proxy to endogenise this relationship.

The model determines $PMT_{t,d}$ and $tti_{t,d}$ subject to:

Minimise $C = \sum_{t,d} PMT_{t,d} \cdot c_{t,d}$, \hspace{2cm} (Equation 1)

where $PMT_{t,d}$ is the travel demand of technology $t$ for long or short demand $d$ and cost is the sum of fuel, investment, O&M and TTI cost:

$c_{t,d} = f_{t,d} + i_{t,d} + om_{t,d} + tc_{t,d}$; \hspace{2cm} (Equation 2)

where fuel cost $f_{t,d}$ is a product of the price per unit of energy of fuel and the energy intensity by technology, divided by the load factor:

$f_{t,d} = (F \cdot int_{t,d}) \div LF$; \hspace{2cm} (Equation 3)

and the cost of travel time investment $tti_{t,d}$ depends on vehicle speed:

$tc_{t,d} = (tti_{t,d} + s_{t,d}) \cdot i$ \hspace{2cm} (Equation 4)

where $s_{t,d}$ is the speed in miles per hour of technologies and $i$ is the TTI cost;

The model is subject to the constraints:

$\sum_{t} PMT_{t,d} = PMT_{d}$ for long and short demand $d$ \hspace{2cm} (Equation 5)
We may also constrain the model to meet a CO$_2$ target $X$:

$$\sum_{t,d} PMT_{t,d} \cdot e_{t,d} \leq X \tag{Equation 7}$$

where $e_{t,d}$ is the emissions in gCO$_2$/PMT of each technology, which is given by the fuel emissions factor, technology efficiency and mode load factor.

### 2.2 TIMES Implementation

In TIMES models the transport sector typically comprises a stock of technologies, in competition, that contribute to meet each exogenously defined modal travel demands (in passenger miles travelled–PMT). Figure 3 shows an example of this approach in the form of Reference Energy System extracted from current Irish TIMES passenger transport sector (Ó Gallachóir et al. 2011). An equivalent structure characterizes the CA-TIMES model.

**Figure 3 – Reference Energy System for Irish TIMES passenger travel sector. Here technologies can compete within modes but not between modes.**

Within the new Reference Energy System, as shown in Figure 4, we introduce just two travel demand commodities: long distance demand (TLDD) and short distance
demand (TSDD) expressed in PMT/year. In order to produce energy service demands all technologies such cars, trains and buses have two inputs: the fuel input and the time input. Here the TIME input describes the travel time from origin to destination, which is dependent on the modal speed, waiting and transfer time. This depends on technology, infrastructure, reliability, congestion, accessibility, etc. The Travel Time Budget (TTB) is exogenously defined in a similar way to demand growth. The model uses Travel Time Investment (TTI) as discussed in Section 2.1.

Figure 4 – Proposed Reference Energy System

3 Case study

3.1 Data sources
We use data from California, U.S., in this simple modelling exercise to examine the modal switch between different modes of travel. Passenger cars are predominantly used as the preferred mode of transport in California. Public transit, that includes all the commuter trains and buses in the state, comprises about 10% of the total demand (California Dept. of Transportation 2002). The passenger miles travelled (PMT) in the state for all the modes are split between long distance and short distance demands.
The short distance demands are captured from the trips within the metropolitan areas in the state, with population greater than 1 million. Table 1 lists the data sources for the attributes used in this model.

**Table 1: Data Sources for the California Modal Share model**

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Person trips by mode and average trip distances per person in each region in CA</td>
<td>2009 National Household Travel Survey, 2010 California Household Travel Survey</td>
</tr>
<tr>
<td>Travel time for public transit (including waiting time and transfer time)</td>
<td>National Highway Institute of Federal Highway Administration, U.S. Bureau of Transportation Statistics</td>
</tr>
<tr>
<td>California population estimates</td>
<td>U.S. Census Bureau</td>
</tr>
<tr>
<td>Load factors and availability factors for transit modes</td>
<td>National Transit Database of Federal Transit Administration</td>
</tr>
</tbody>
</table>

**3.2 TIMES results for TTB model**

The modal-share model is run for several scenarios for California region. Table 2 gives the descriptions of all the scenarios of this modelling exercise.

**Table 2. List of model scenarios in the California modal-share model**

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>No TTB limit</td>
<td>This scenario imposes no TTB constraint. Allows competition between modes based on technology and fuel costs only.</td>
</tr>
<tr>
<td>Reference case</td>
<td>This scenario uses constant TTB per capita over the time horizon. Competition between modes is based on time in addition to cost.</td>
</tr>
<tr>
<td>Introducing TTI</td>
<td>Different levels of TTI are modelled as a proxy for investments to reduce travel time.</td>
</tr>
<tr>
<td>CO₂ constraint</td>
<td>This scenario includes a 20% CO₂ emissions reduction by 2020 to the above scenarios.</td>
</tr>
</tbody>
</table>

**3.2.1 No limit on Travel Time Budget:**

This scenario represents the outcome of standard TIMES model structure. The model is first run without the limit on travel time budget, which implies the
passenger has no bound on how much time one has to choose to travel. The model allows choosing freely between modes, only using the technology and fuel costs. As shown in the Figure 6, the model immediately switches to the bus technology, which is the slower mode of transport, once the existing car capacity is used up.

3.2.2. Reference Case:
A constant travel time budget is introduced into the model based on the annual passenger miles travelled data. Now, the modes compete based on time in addition to other costs. The passenger now has to accommodate the modes of travel within a time constraint, this pushes the model to choose faster modes of travel within the given time budget. This is shown in Figure 5. At present, TTB grows at the same rate as transport demand. In the past, demand has grown at a faster rate than TTB (Figure 2): This scenario favours faster modes, and this will be investigated further in future refinements of the model.

3.2.3. Introducing TTI:
Various levels of TTI are introduced in the model to reduce the total travel time for the passenger. High and low time travel costs are introduced. It is observed that, when the investment cost for the additional time is low, the model invests in time, and switches to the slower modes such as buses and trains. However, as the investment cost for the time increases, the results resemble the reference case scenario. Figure 6 shows the scenarios of various levels of TTI.
3.2.5. Carbon Emissions Constraint:

A 20% CO\textsubscript{2} emissions reduction constraint is included for the model runs for the various scenarios discussed above. It is observed that, the emissions constraint scenarios choose public transit at a higher rate than the scenarios without the emissions constraint. Figure 7 illustrates a scenario with a carbon constraint and a high cost of investment into TTI.
4 Discussion

The modal shift modelling methodology and simple TIMES model presented here are a significant and novel step towards incorporating behaviour into energy systems models.

At present, the TTI variable is a proxy for the cost of investment that increases the speed of modes. We intend to further investigate this variable and endogenise the relationship between investment in infrastructure and reduced travel time. We also intend to incorporate elasticities with regard to demand and to simulate the response in demand of one mode to the changes in the attributes of others.

The representation of technology in the model is currently limited, with four technologies and two fuels. We intend to expand the model to include a full range of transport technologies in order to investigate the trade offs between modal shifting and investment into alternatively fuelled vehicles under a range of scenarios. This methodology will then be incorporated into the Irish and California TIMES models to capture the interactions with the energy system as a whole.

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