Designing a road traffic model for the cross-sectoral analysis of future national infrastructure

Milan Lovrić
University of Southampton

Simon Blainey
University of Southampton

John Preston
University of Southampton

Abstract (max 500 words)

This paper presents a UK national road traffic model developed as part of the ITRC MISTRAL - a large interdisciplinary project of the Infrastructure Transitions Research Consortium (ITRC). The proposed model includes passenger and freight vehicle flows on major UK roads and predicts future demand in the form of an inter-zonal origin-destination matrix, using and elasticity-based simulation approach. An important part of the model is the network assignment step during which predicted flows are assigned to the road network. This allows for the assessment of road capacity utilisation and facilitates the identification of "pinch points" where future infrastructure investments might be targeted. Several policy interventions are studied in the paper, including road expansion with additional lanes, new road development and vehicle electrification. The model also explicitly considers cross-sectoral interdependencies with other infrastructure networks, primarily with the energy sector where the transport sector is the largest consumer, the digital communications sector, water supply and waste management. In future extensions, the model will also be able to estimate the environmental footprint and assess the risk and resilience of the transport network. This model has the potential to inform policy makers about the long-term performance of UK road infrastructure, considering a range of possible future scenarios for population growth, technological innovation and climate change.

Key Words

Transport modelling; road traffic; national infrastructure; cross-sectoral analysis; elasticity-based simulation; demand modelling; capacity utilisation; policy making.

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Minimum 4 pages (1600 words) and maximum 10 pages (5000 words)

1. Introduction

The UK Infrastructure Transitions Research Consortium (ITRC) is a consortium of seven leading UK universities, established in 2011 with the vision for infrastructure decisions to be guided by systems analysis. ITRC aims to provide policy makers with a range of models that can inform them how infrastructure systems are performing, how resilient or vulnerable they are, and how infrastructure investments can be evaluated under a range of possible future scenarios including population growth, new technologies and climate change. During the first EPSRC Programme Grant (2011-2015), the ITRC has delivered the world's first family of national infrastructure system models (NISMOD) for analysis and long-term planning of interdependent infrastructure systems[1]. This research is already being used by the UK government to analyse the National Infrastructure Plan and inform better infrastructure decisions. MISTRAL (Multi-scale Infrastructure Systems Analytics) is the second major ITRC project funded by the EPSRC Programme Grant (2016-2020). Its aim is to further develop and extend the infrastructure systems analysis capability of NISMOD: *downscale* (to a finer representation of national infrastructure services and networks), *upscale* (to incorporate global interconnections at model boundaries) and *across-scale* (to other national settings outside the UK).

A range of strategic, long-term transport models has been previously developed in Great Britain[2],[3],[4],[5],[6],[7],[8],[9] and several other countries[10],[11],[12],[13]. However, the initial review of these studies found that they were unsuitable for the aims of the ITRC project, because either they were not able to offer flexible scenario capabilities or they were unable to provide a national multimodal coverage with

[1] Hall, J. W., Tran, M., Hickford, A. J., Nicholls, R. J. (Eds.). The Future of National Infrastructure: A System-of-Systems Approach. Cambridge University Press. (2016).

[2] URS and Scott Wilson. Modelling longer distance demand for travel phase 3: Final Report – Volume 1 Main Report. URS/Scott Wilson. Basingstoke, UK. (2011).

[3] Department for Transport. National Transport Model: High Level Overview. London, UK, DfT. (2009).

[4] HS2 Ltd. High Speed Rail – London to the West Midlands and beyond: HS2 demand model analysis. London, UK, HS2 Ltd. (2010).

[5] WSP Group. NTEM Planning Data version 6.2: Guidance Note. London, UK, Department for Transport. (2011).

[6] MDS Transmodal Ltd. GBFM Version 5.0 report. MDS Transmodal Ltd. (2008).

[7] Steer Davies Gleave and DeltaRail. Network Modelling Framework – background documentation: overview document. Scotland. London, UK, DfT, ORR, Transport. (2007).

[8] Department for Transport. UK Aviation Forecasts. London: DfT. (2011).

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[10] Arnold, M., Hajos. B., Busch, T. Long term demand and financial forecast methodology for a large scale regional public transport network in Germany. European Transport Conference. Frankfurt, Germany. (2013).

[11] Gusbin, D., Hoornaert, B., Mayeres, I., Nautet, M. The PLANET model methodological report: modelling of short sea shipping and bus-tram-metro. Brussels, Belgium, Federal Planning Bureau. (2010).

[12] Van der Hoorn, T., van Wee, B. Transportation models and their application. In van Wee, B., Annema, J.A. and Banister, D. (Eds). The Transport System and Transport Policy: An Introduction. Edward Elgar, Cheltenham. (2013).

[13] Stephenson, J., Zheng, L. National long-term land transport demand model. Wellington, New Zealand, NZ Transport Agency. (2013).

efficient simulation run times. It was therefore decided to develop a bespoke ITRC transport model (NISMOD-LP-T). This model is able to generate macro-scale spatially disaggregated forecasts of multimodal transport demand, capacity, emissions and costs for the Great Britain down to a scale of local authority districts. Although this transport model has generated a range of useful insights[14] and contributed to a work for the Infrastructure UK and the National Infrastructure Commission (NIC), it has some limitations which render it less adequate for future work. For example, the model is characterised by a lack of an origin-destination (OD) matrix, relatively low resolution of transport network representation, a limited representation of intermodal competition, and no integration with the infrastructure network risk models (NISMOD-RV) developed during ITRC at the University of Oxford. The MISTRAL transport model aims to address those limitations and include further capabilities, such as: explicit cross-sectoral interdependencies (with the energy sector, digital communications, solid waste and water supply), global interconnectivity (with international demand and supply nodes), and a wide range of policy instruments related to infrastructure and its use.

2. MISTRAL road traffic model

This section describes the design of the road traffic model which is being developed as a part of the MISTRAL transport model. Road traffic model includes two demand prediction models: for *passenger* vehicles (cars) and for *freight* vehicles (vans, rigids and artics). An earlier version of the road traffic model was reported in the Fast-Track case study[15].

2.1. Model inputs

The main input for the demand model is a base-year (2015) origin-destination matrix for inter- and intra-zonal road traffic. Unfortunately, no suitable existing matrix is readily available for passenger car traffic, but a range of data does exist which could form the basis for matrix estimation. Tempro data provides estimates of passenger trip generation and attraction for 2,496 zones covering the whole of Great Britain. Furthermore, there is an Average Annual Daily Flow (AADF) traffic count data for the major road network, disaggregated into 17,900 links, available from the DfT[16]. The initial OD matrix for passenger

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[14] Hickford, A. J., Nicholls, R. J., Otto, A., Hall, J. W., Blainey, S. P., Tran, M., Baruah, P. Creating an ensemble of future strategies for national infrastructure provision. Futures, 66, 13–24. (2015).

[15] Lovrić, M., Blainey, S., Preston, J. A conceptual design for a national transport model with cross-sectoral interdependencies. EURO Working Group on Transportation Meeting (EWGT). Budapest. (2017).

[16] Department for Transport. Road Traffic Estimates: Methodology Note. London, UK, DfT. (2010).

cars has been created by iterative scaling using the Tempro data and an observed trip-length distribution. This matrix will need to be further refined when the model is calibrated with AADF traffic counts.

Origin-destination matrix for freight traffic is already available from DfT's Base Year Freight Matrices (BYFM) study[17], so it was only necessary to scale flows from year 2006 to 2015. This data consists of the number of freight vehicles per average day between origin-destination zone pairs, divided into three vehicle categories: artics, rigids and vans. Freight zones in the BYFM study can be either spatial zones (local authority districts) or location points (major distribution centres, airports and seaports).

In addition to OD matrices, the demand model also requires data on population and Gross Value Added (GVA) in local authority districts, including their predictions for future years. These predictions could be generated as hypothetical scenarios (e.g., low/central/high population growth). This study, however, uses population and GVA projections by the World Bank.

2.2. Demand model

The demand model captures the impact of endogenous and exogenous factors on transport demand using an elasticity-based simulation methodology, similar to the original ITRC transport model. The demand (inter- and intra-zonal vehicle flows) is predicted using the following equation:

$$F_{ijy} = F_{ijy-1} \left(\frac{P_{iy}}{P_{iy-1}}\right)^{\eta_P} \left(\frac{I_{iy}}{I_{iy-1}}\right)^{\eta_I} \left(\frac{P_{jy}}{P_{jy-1}}\right)^{\eta_P} \left(\frac{I_{jy}}{I_{jy-1}}\right)^{\eta_I} \left(\frac{T_{ijy}}{T_{ijy-1}}\right)^{\eta_T} \left(\frac{C_{ijy}}{C_{ijy-1}}\right)^{\eta_C} \tag{1}$$

Where:

- F_{ijy} is the flow between zone *i* and zone *j* in year *y*.
- P_{iy} is the population in zone *i* in year *y*.
- I_{iy} is the Gross Value Added (GVA) per head of population in zone *i* in year *y*.
- T_{ijy} is average travel time between zone *i* and zone *j*.
- C_{ijy} is average fuel cost between zone *i* and zone *j*.
- Elasticity parameters η have been taken from previous studies (Table 1).

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[17] Department for Transport. Base Year Freight Matrices. Final Report. Contract PPRO 04/03/14. London, UK, DfT. (2014).

Passenger demand (passenger car flows) and freight demand (freight vehicle flows) are predicted using the same equation and somewhat different inputs (different values of elasticity parameters and different time and cost skim matrices, computed separately for freight vehicles).

Table 1: Parameterisation of demand models.

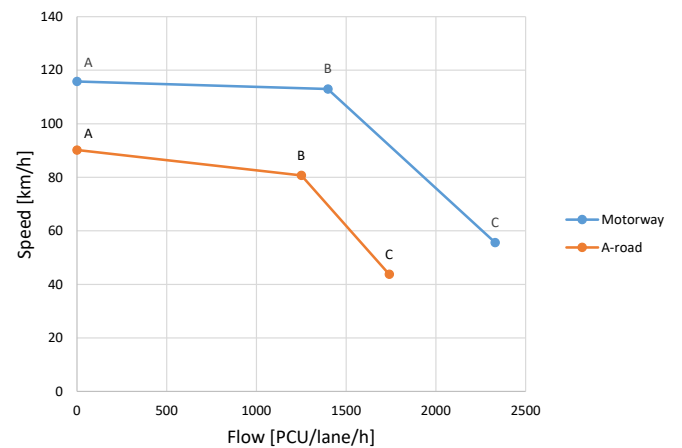| Parameter	Description	Value	Value (freight)
η_P	Elasticity of population	1.0	1.0
η_I	Elasticity of GVA	0.63	0.7
η_T	Elasticity of time	-0.41	-0.41
η_C	Elasticity of cost	-0.215	-0.1

Figure 1: Speed-flow relationship for UK roads.

2.3. Network assignment

The new model is explicitly network-based in that a network assignment step is used to jointly assign passenger and freight vehicle flows to the AADF representation of the UK major road network consisting of motorways and A-roads (Figure 2). Once the predicted flows from the demand model are assigned to the network, new inter- and intra-zonal travel costs and times can be computed, and these can feed back into the demand estimation equation. Network assignment is also used to output the levels of capacity utilisation and other performance indicators, and in such a way it can help identify infrastructure "pinch points" that may be targeted by various policy interventions.

Network assignment is a computationally expensive step that involves routing between origin and destination using path-finding algorithms. The first iteration of network assignment is based on free-flow link travel times, which are calculated from link distances and free-flow speeds for each road category. The subsequent iterations of network assignment are based on congested link travel times calculated from simulated peak-hour capacity utilisation and empirical speed-flow curves (see section 2.4). In the current implementation, the number of iterations is restricted to a fixed number so as to limit the total execution time. However, future implementations might consider other, more formal, stopping criteria.

Since local authority districts represent relatively large zones compared to the road network, it was necessary to first determine trip start and trip end nodes (road intersections) within each district. This was achieved by using a finer spatial zoning system of census output areas (for passenger demand) and workplace zones (for freight demand) to determine the size of the residential (or workplace) population that gravitates to each network node. Origin and destination nodes were then chosen probabilistically based on the size of the gravitating population. The fastest path between origin and destination nodes was found using a heuristic search algorithm (A*) and congested (initially, free-flow) link travel times used as edge weights. The chosen path was saved into a path storage, which was later used to update cost matrices (see section 2.5) and calculate fuel and electricity consumptions.

2.4. Link travel time

Link travel times are updated using the speed-flow relationship from the DfT's FORGE model[18]. Total daily volume on each link was expressed in Passenger Car Unit (PCU) equivalents (1 car = 1 PCU, 1 van = 1 PCU, 1 artic = 2 PCU, 1 rigid = 2 PCU) and peak-hour volume was obtained as a 10.322% of total daily volume, based on the distribution of car driver trips over an average weekday from the National Travel Survey[19]. A simplifying assumption was made that motorways have three lanes in each direction and that A-roads have one lane in each direction (single carriageway). Once the flow is determined, the link travel time can be calculated from the peak-hour speed and the link length.

2.5. Skim matrix (time and cost)

Skim matrices represent inter- and intra-zonal travel times and travel costs. Travel times are computed after the network assignment step, as an average (congested) travel time across all the paths travelled between an origin and a destination zone. Similarly, travel costs are calculated as average fuel cost across all the paths travelled between an origin and a destination zone. These costs are computed assuming a fixed vehicle split over different engine types (petrol, diesel, LPG, hydrogen, electric) and taking into account engine consumptions and unit fuel costs (unit electricity cost is an input from, i.e., an interdependency with, the energy sector).

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[18] Department for Transport. National Transport Model: FORGE The Road Capacity & Costs Model. London, UK, DfT. (2005).

[19] Department for Transport. National Travel Survey Table NTS0501. London, UK, DfT. (2010).

2.6. Model outputs

The road traffic model produces the following outputs:

- Predicted origin-destination (OD) matrix for road traffic (passenger and freight separately).

- Predicted travel time skim matrix (passenger and freight separately).

- Predicted travel cost skim matrix (passenger and freight separately).

- Predicted congested (peak-hour) link travel times.

- Predicted (peak-hour) capacity utilisation of road links (Figure 3). These were calculated by dividing simulated peak-hour flows with maximum capacities for different road types.

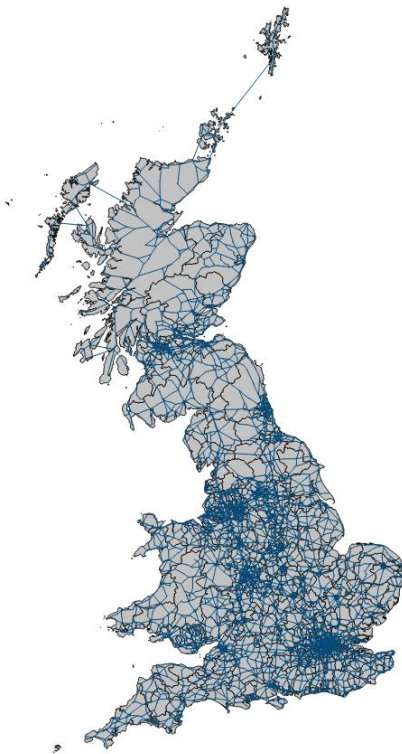- Predicted electricity and fuel consumptions.
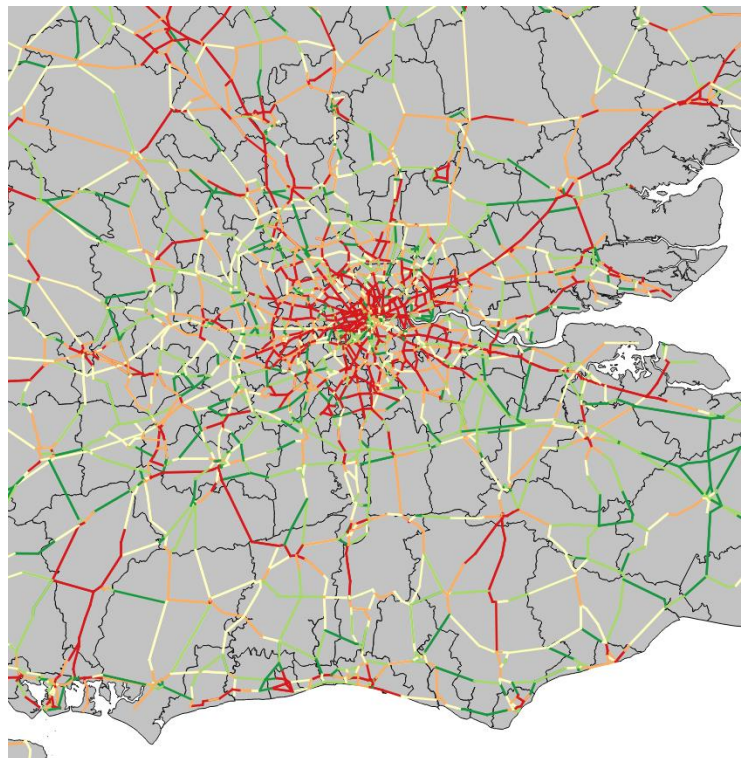

Figure 2: UK major road network.

Figure 3: Road capacity utilisation (base-year simulation).

2.7. Transport sector and its cross-sectoral interdependencies

Being one of the largest energy consumer, the transport sector has very strong links with the energy sector. Conversely, transport demand is also highly dependent on the energy prices. It is expected that a shift towards electric vehicles in the coming years will vastly change the type of energy demanded. The advances in transport technology and services (e.g. autonomous vehicles, V2V communication, mobility as a service) are also expected to increase the demand for bandwidth provided by the digital communications sector. The transport model has some dependency on the water supply sector, because road infrastructure could be affected by flooding which can cause major disruptions. The network assignment step allows for the specification of blocked road links, which can already accommodate many potential causes of disruptions. However, an integrated cross-sectoral interface covering disruption risks is under development in conjunction with the ITRC risk modelling team. Finally, the transport model is dependent on the outputs from the solid waste sector because solid waste requires transportation and therefore affects the demand for freight, both at a domestic and an international level.

2.8. Policy interventions

In this study, three policy interventions have been considered and implemented:

- *Road expansion* – this intervention increases the capacity of existing road links by building new lanes.
- *Road development* – this intervention builds a completely new road link between two existing intersections.
- *Vehicle electrification* – this intervention proposes a higher share of electric vehicles in the engine type split.
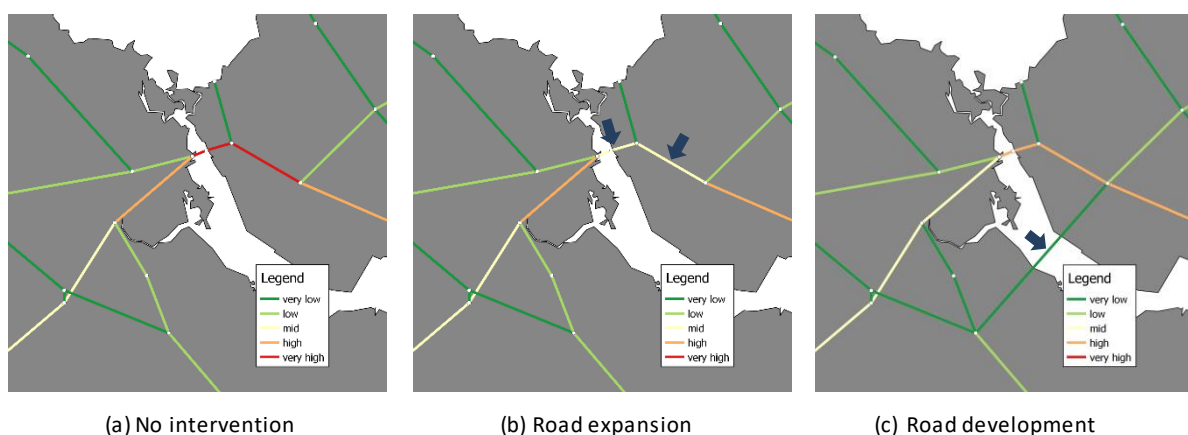

(a) No intervention   (b) Road expansion   (c) Road development

Figure 4: Predicted road capacity utilisation after different types of policy interventions.

3. Results and discussion

Figure 4 shows the impact of different types of policy interventions on road capacity utilisation. Figure 4a shows predicted road capacity utilisation, with red links suggesting the "pinch points" with highest levels of peak-hour congestion. To target this area, a road expansion policy (Figure 4b) was implemented to add an additional lane (in each direction) to the most congested links. This policy had a strong effect of reducing the capacity utilisation of expanded roads, but its effect was rather localised. Road development policy (Figure 4c) created a completely new road link between two existing intersections. This policy also reduced capacity utilisation in the "pinch point" areas, but not as effectively as the road expansion policy. However, by providing an alternative route, this policy had a more widespread effect of reducing capacity utilisation on more road links.
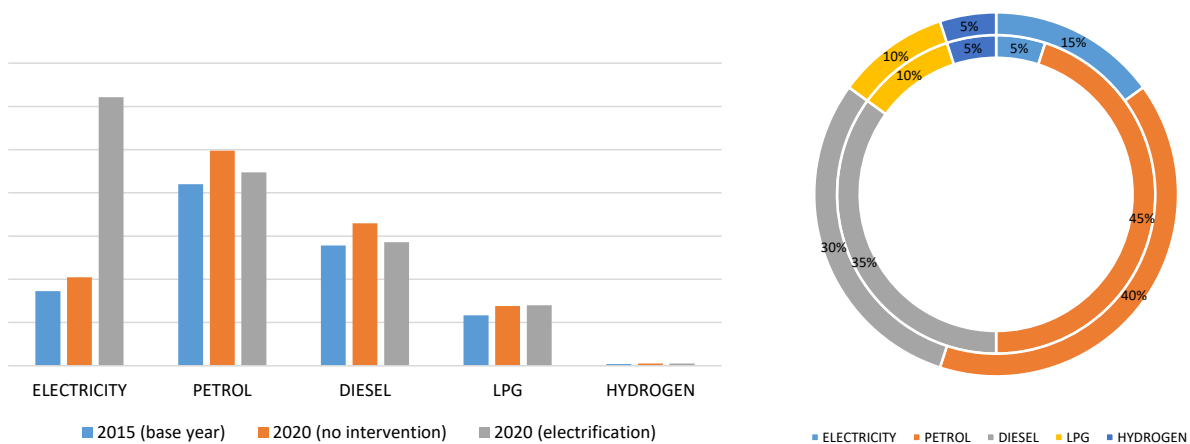
(a) Predicted car consumptions (electricity and different fuel types) (b) Car fuel type shares (before/after electrification)

Figure 5: Vehicle electrification policy intervention.

Figure 5a shows total car electricity/fuel consumptions in the base year (2015) and predictions for 2020, with and without the policy intervention of vehicle electrification. In our implementation, the vehicle electrification policy entails increasing the share of electric vehicles from 5% to 15% at expense of petrol and diesel engines, while the shares of LPG and hydrogen are remaining the same (Figure 5b). Without the vehicle electrification policy, there was an increase in all consumptions driven by the growth in population and GVA. With the electrification policy, there was a marked increase in the electricity consumption (around 260%), which is going to put a large demand on the energy sector.

With electrification policy in place, there was also an increase in diesel and petrol consumptions, but demand for those fuels grew slower than in the case of no policy intervention. Vehicle electrification policy is also expected to have considerable environmental implications, which will be assessed once the environmental module is implemented.

4. Conclusions

This paper presents the design and preliminary results of a UK road traffic model for the cross-sectoral analysis of future infrastructure. The demand prediction model (for passenger and freight vehicle flows) was developed using an elasticity-based framework. The network assignment is based on a major UK road network (including motorways and A-roads), routing with a heuristic search algorithm, and population data in fine spatial zoning systems of census output areas and workplace zones. Network assignment is an important component of the new MISTRAL transport model as it allows a link-based assessment of capacity utilisation and an identification of the "pinch points" which may be targeted by various policy interventions. Two interventions for increasing road capacity were presented in this paper: road expansion with new lanes and new road development. This paper also presented a vehicle electrification intervention, which is expected to profoundly impact future energy consumptions and the interdependencies between the transport and the energy sector. In future work, the presented road traffic model will be refined with more realistic behavioural models and implementations, optimised for speed, and calibrated using traffic count data.