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A conceptual design for a national transport model with cross-sectoral interdependencies

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Abstract

This paper presents issues, trade-offs and challenges encountered while developing a UK national transport model as part of a large interdisciplinary project, ITRC MISTRAL. The Infrastructure Transitions Research Consortium (ITRC) is a consortium of seven leading UK universities focusing on analysis of national infrastructure systems using a system-of-systems approach. In this paper, we describe a multi-modal multi-scale national transport model being developed by ITRC which includes passenger and freight transport via highways, railways, airports, seaports and local transit networks. The model predicts future demand for each mode on individual flows using an elasticity-based simulation approach. These flows are then assigned to transport networks to assess infrastructure capacity utilisation and obtain new estimates of inter-zonal travel times. The model explicitly considers cross-sectoral interdependencies with other infrastructure networks, including the energy sector (where transport is the largest consuming sector), digital communications (which provide bandwidth to passengers and enable smart mobility), waste management (which requires transport services) and water supply (where flooding poses a major risk of transport disruptions). It is also planned to be capable of estimating environmental emissions and assessing the vulnerability and resilience to risk of transport systems. The enhanced transport model discussed here builds on an existing modelling framework which has been used by the UK government to inform their National Infrastructure Assessment. As such, the model has the potential to support policy making with regards to infrastructure investment on a decadal scale, under a range of possible future scenarios including population growth, new technologies and climate change.

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Keywords: transport modelling; national infrastructure; cross-sectoral analysis; elasticity-based simulation; demand modelling; capacity utilisation; railways; traffic; airports; seaports; freight; policy making.

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1. Introduction

1.1. Background to MISTRAL

National infrastructure provides key services to a modern economy including: energy, transport, digital communications, water supply, and waste management. The UK's National Infrastructure Plan, outlining the vision for the future of UK infrastructure, set out over £460 billion of investment in the next decade. However, at this stage, little is known of how this investment will impact the performance of national infrastructure services and how it will influence economy, society and the environment. The complexity of infrastructure networks and their interactions with people, economy and the environment means that infrastructure planning often involves a lot of guesswork. The UK Infrastructure Transitions Research Consortium (ITRC) is a consortium of seven UK universities, established in 2011 with the vision for infrastructure decisions to be guided primarily by systems analysis. When this vision is achieved, decision makers will have a range of models at their disposal that will tell them how all infrastructure systems are performing. They will also be able to assess the resilience and vulnerabilities of infrastructure, and evaluate investment decisions under a range of future scenarios including population growth, new technologies and climate change. Thanks to the first EPSRC Programme Grant (2011-2015), the ITRC has developed and demonstrated the world's first family of national infrastructure system models (NISMOD) for analysis and long-term planning of interdependent infrastructure systems (Hall et al., 2016). The 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), whose aim is to develop and demonstrate a highly integrated analytics capability to inform strategic infrastructure decision making across scales, from local to global. MISTRAL will thereby extend infrastructure systems analysis capability: 1) Downscale: from ITRC's representation of national networks to the UK's 25.7 million households and 5.2 million businesses, representing the infrastructure services they demand and the multi-scale networks through which these services are delivered; 2) Upscale: from the national perspective to incorporate global interconnections via telecommunications, transport and energy networks; 3) Across-scale: to other national settings outside the UK, where infrastructure needs are greatest. These research challenges need to be tackled because infrastructure systems are interconnected across scales and technological innovation is now occurring that is expected to influence their interconnectedness. MISTRAL aims to quantify these opportunities and risks, providing the evidence needed to plan, design, and invest in sustainable and resilient infrastructure.

1.2. Brief review of existing strategic models

A range of strategic transport models have been developed previously in a number of countries around the world. These include, for example, the long-term public transport model created for the Rhine/Main Regional Transport Association in Germany (Arnold et al., 2013), the Belgian Federal Planning Bureau's PLANET transport demand model (Gusbin et al., 2010), the Dutch National Transport Model (Van der Hoorn and van Wee, 2013), New Zealand's National Long-Term Land Transport Demand Model (Stephenson and Zheng, 2013), passenger and freight transport models developed for Italy (Crissali et al., 2013, Nuzzolo et al., 2013b) and for Europe (De Jong et al., 2004, De Jong et al., 2012, Nuzzolo et al., 2013a).

In Great Britain, there are also a number of existing long-term models, including the Long Distance Model (URS/Scott Wilson, 2011), the National Transport Model (NTM) (Department for Transport, 2009), the PLANET Long Distance model (HS2 Ltd, 2010), the National Trip End Model (WSP Group, 2011), the Great Britain Freight Model (MDS Transmodal Ltd., 2008), the rail Network Modelling Framework (Steer Davies Gleave and DeltaRail, 2007), the Air Passenger Demand Model (Department for Transport, 2011a), and the National Air Passenger Allocation Model (Department for Transport, 2011b). However, the review of these models found that they were unsuitable for the ITRC project because, for example, they did not cover the full study period (2011-2100), or they were not able to offer the national multi-modal coverage, efficient runtimes and flexible scenario capability required by the project. Therefore, a bespoke model (NISMOD-LP-T) was developed. This model generates macro-scale spatially-disaggregated forecasts of multimodal transport demand, capacity, emissions and costs for the whole of Britain down to a local-authority scale.

1.3. Brief overview of previous model's limitations and aspirations for MISTRAL

The MISTRAL transport modelling work will build on the transport model developed at the University of Southampton during the first ITRC project (NISMOD-LP-Transport) and the transport risk modelling work carried out during ITRC at the University of Oxford (components of NISMOD-RV). The transport model has generated a range of useful insights (Hickford et al., 2015) as well as contributed to work for the Infrastructure UK and the National Infrastructure Commission (NIC). However, it has some inherent limitations (described below) which place restrictions on its usefulness for future work. For example, the old ITRC transport model is characterised by:

- Lack of an OD matrix.
- Limited representation of intermodal competition.
- Relatively low resolution of transport network representation.
- No integration with the infrastructure network risk models (NISMOD-RV).

The MISTRAL transport model aims to address those limitations by fulfilling the following requirements:

- Development of new demand/capacity models for road, rail, sea and air traffic
  - Based on OD matrices and network assignment.
- Cross-sectoral interdependencies:
  - With energy sector, digital communications, solid waste and water supply (see Section 2).
- Local transport:
  - Representation of urban public transport such as underground, light rail, bus rapid transit etc.
- Global interconnectivity:
  - Integration with international demand/supply nodes at model boundaries.
- System model which can look at packages of investments and policy instruments, e.g.:
  - Increased road capacity and/or new road development.
  - Electrification of vehicles.
  - New bus and rail services (e.g. high-speed rail).
  - New technologies and modes (e.g. autonomous vehicles on demand).
  - Congestion charging on roads and off-peak pricing in public transit.
- Modelling of disruption effects:
  - E.g. due to floods or power outage.
- Integration of capacity/demand and risk modelling frameworks:
  - Identification of most vulnerable point on networks and impact of interventions to increase resilience.
- Environmental emissions:
  - Assessment of transport sector's environmental footprint including CO2 and particulate emissions.

2. Transport sector and its cross-sectoral interdependencies

Fig. 1. shows the links between the transport sector and other infrastructure sectors (energy, digital communications, water supply and solid waste). The Transport sector (TR) has strong links with the Energy sector (E), not only as one of the largest energy consumers, but also with transport demand being linked to energy prices. Transport systems are also susceptible to disruptions caused by power outages and energy shortages. Moreover, the energy sector is dependent on future developments in the transport sector, as a shift towards electric vehicles and electrified railways is expected to vastly change the type of energy demanded.

Digital Communications (DC) can affect demand for transport, both positively and negatively. By facilitating remote working, it could reduce transport demand, whilst by facilitating a shift towards mobility as a service (MaaS) and providing technologies that make transport more accessible, changes in Digital Communications could increase transport demand. Transport can also affect demand for bandwidth, especially along transport corridors. This could increase markedly due to technologies which require connected systems and data provision (e.g. autonomous vehicles and V2V communication), and a demand for communication as people travel (e.g. on rail).

The transport model has some dependency on the Water Supply sector (WS), because road and rail infrastructure could be affected by flooding which can cause major disruptions. To understand these impacts, transport infrastructure needs to be modelled at a high enough resolution to identify roads and railways that lie within flood risk areas.

The transport model is also dependent on outputs from the Solid Waste sector (SW) because solid waste requires transportation and therefore affects the demand for freight, both at a domestic and an international level (solid waste is often exported through UK sea ports).

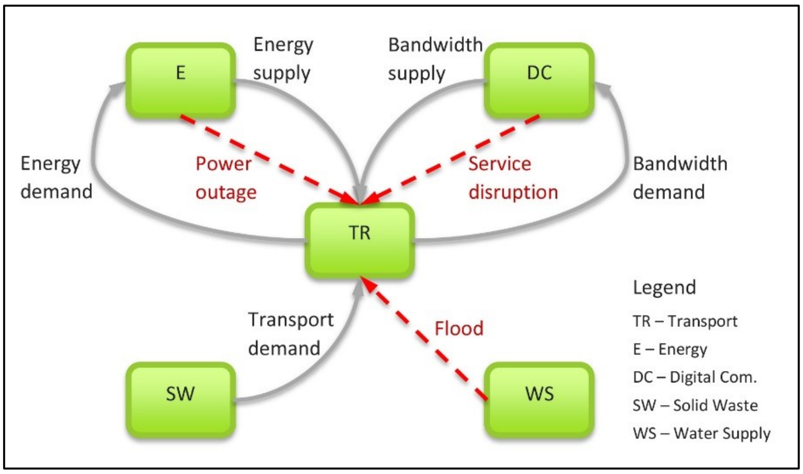

Fig. 1. Diagram of cross-sectoral interdependencies with the Transport sector.

3. Planned structure for MISTRAL transport model and the Fast-Track case study

This section describes the planned structure for MISTRAL transport model and more specific modelling choices made during the Fast-Track case study. The Fast-Track case study focuses on highway traffic in a small region of South-East England including four local authority districts: Southampton, New Forest, Eastleigh and Isle of Wight. Two demand prediction models were developed for the case study; one for passenger vehicles (cars) and the other for freight vehicles (vans, rigids and artics).

3.1. Model Inputs

The first modelling task involves the development of a base-year OD matrix for road, rail and air traffic to provide an input for the demand model. This matrix should map onto a spatial zoning system based on local authority districts. An OD matrix is already available from Civil Aviation Authority statistics for air traffic, and an OD matrix for passenger rail travel is contained in the Department for Transport (DfT) owned RUDD dataset. Similarly, a rail freight OD matrix will be constructed based on electronic timetable data. Data on OD flows for freight traffic is available from DfT's Base Year Freight Matrices (BYFM) 2006 study (Department for Transport, 2014). This data consists of the number of freight vehicles per average day between a set of origin-destination zone pairs, divided into three vehicle categories: artics, rigids and vans.

Unfortunately, no suitable existing matrix is readily available for road traffic, but a range of data does exist which could form the basis for such a matrix. Tempro data provides estimates of passenger trip generation and attraction for 2,496 zones covering England, Wales and Scotland. This is complimented by Average Annual Daily Flow (AADF) traffic count data for the major road network, disaggregated into 17,900 links, which is available from the DfT (Department for Transport, 2010a). A significant proportion of the work in this task will therefore involve estimating an OD matrix based on the Tempro and AADF datasets.

Underground and light rail networks will be treated in the same way as the national rail network, although detailed data on passenger numbers may not be available for all light rail networks. Local public transport will be represented to a degree that was not possible with the ITRC model. Comprehensive bus timetable data is available from data.gov.uk, and will be used together with DfT statistics and AADF data (which includes buses) to create a base bus network, which will then be treated as a separate mode but using the same infrastructure as other road traffic. Walking and cycling will be modelled on an intra-zonal basis measured as a total number of trips per zone, with initial trip rates estimated based on National Travel Survey (NTS) and census data.

In addition to a zoning system internal to Great Britain, we will need to develop an external zoning system with some relatively fine scale zones (e.g. Northern Ireland, Channel Islands) but which get coarser in scale as we move away from Great Britain. International air, rail, road and sea traffic will be allocated to these zones. We will identify international gateways based around the airports and seaports in the ITRC model and load the access/egress traffic onto the internal links.

3.2. Demand Model

The demand model is capturing the impact of endogenous and exogenous factors on transport demand using an elasticity-based simulation methodology similar to the original ITRC transport model. The model, however, is explicitly network-based in that a network assignment step is used to obtain an estimation of inter/intra-zonal travel costs and times which are feeding back into the demand estimation. Network assignment is also used to output the levels of capacity utilisation and other performance indicators.

The first stage of estimating demand in year *i* involves applying an equation of the general form (1) to each flow contained in the OD matrix:

$$F_{ijmy} = F_{ijmy-1} \prod_{A} \left(\frac{a_{iy}}{a_{iy-1}}\right)^{\eta_a} \prod_{B} \left(\frac{b_{jy}}{b_{jy-1}}\right)^{\eta_b} \prod_{C} \left(\frac{c_{ijy}}{c_{ijy-1}}\right)^{\eta_c} \tag{1}$$

Where:

- F_{ijm} is the number of trips from zone i to zone j by mode m.
- y is the year for which traffic is being forecast.
- y-1 is the preceding year.
- A is the set of variables which affect trip generation in the origin zone i.
  - Examples: population, economic activity, level of technology provided, manufacturing (for freight).
  - Other examples from the literature: household size, household structure, income, car ownership, residential density, accessibility etc.
- B is the set of variables which affect trip attraction in the destination zone j.
  - Examples from the literature: land-use and employment by category (e.g. industrial, commercial, services), accessibility etc.
- C is the set of variables which affect the cost of travel by all modes between origin zone i and destination zone j (for each mode this will include the cost of any available alternative modes, which have an impact via the associated demand cross-elasticity).
  - Inter/intra-zonal skim matrix for highway (e.g. travel time, distance, cost, or generalized cost).
  - Inter/intra-zonal skim matrix for transit (e.g. travel time, fare, number of transfers).

- a, b and c are individual variables within sets A, B and C.
- η_a is the elasticity of demand with respect to variable a (and similar).
- The values of elasticities will be taken from the literature.

Passenger demand (passenger vehicle flows) are predicted using the following, more specific, version of the general formula:

$$F_{ijy} = F_{ijy-1} \left(\frac{P_{iy}}{P_{iy-1}}\right)^{\eta_P} \left(\frac{I_{iy}}{I_{iy-1}}\right)^{\eta_I} \left(\frac{P_{jy}}{P_{jy-1}}\right)^{\eta_P} \left(\frac{I_{jy}}{I_{jy-1}}\right)^{\eta_I} \left(\frac{T_{ijy}}{T_{ijy-1}}\right)^{\eta_T} \left(\frac{C_{ijy}}{C_{ijy-1}}\right)^{\eta_C} \quad (2)$$

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 are taken from previous studies (see Table 1).

Freight demand (freight vehicle flows) are predicted using the same formulation as (2), but using somewhat different inputs. Freight zoning system includes local authority districts (as in the passenger demand models) plus freight airports, freight seaports and major distribution centres, as defined in the DfT's Base Year Freight Matrices study (2006). The freight model also uses different values of elasticity parameters (see Table 1) and different time and cost skim matrices, which are computed separately for freight vehicles.

Table 1. Parameterisation of demand models.

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

3.3. Network assignment

Network assignment jointly assigns passenger and freight vehicle flows to the AADF representation of the major road network. Once new traffic volumes have been estimated for each flow in passenger and freight OD matrix, these are then loaded onto to the transport network by connecting origin and destination zones with fastest paths. The first iteration of network assignment is based on free-flow link travel times which are calculated from link distances and maximum speeds for each road category (speed limit on motorways is 70 mph (113 kph), on A roads it is 60 mph (97 kph) and an average ferry speed is assumed to be 30 kph). The subsequent iterations of network assignment are based on congested link travel times that are calculated from peak-hour capacity utilisation (see section 3.4). 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 end locations using a finer spatial zoning system of census output areas (for passenger demand) and workplace zones (for freight demand).

For each trip between origin and destination zone (LAD) the network assignment is implemented as follows:

1. Origin and destination census output areas (or origin and destination workplace zones for freight) are chosen probabilistically based on the population size (see Fig. 2a), with choice probability of each output area (or workplace zone) calculated as the percentage of LAD population living in that area.
2. The chosen census output areas (or workplace zones for freight) are mapped to the road network by linking each area's population-weighted centroid to its nearest network node (see Fig. 2b).
3. The fastest path between origin and destination nodes is found using a heuristic search algorithm (A*) and congested (initially, free-flow) link travel times as edge weights.
4. The chosen path is saved into a path storage, which is later used to update cost matrices and calculate fuel and electricity consumption.

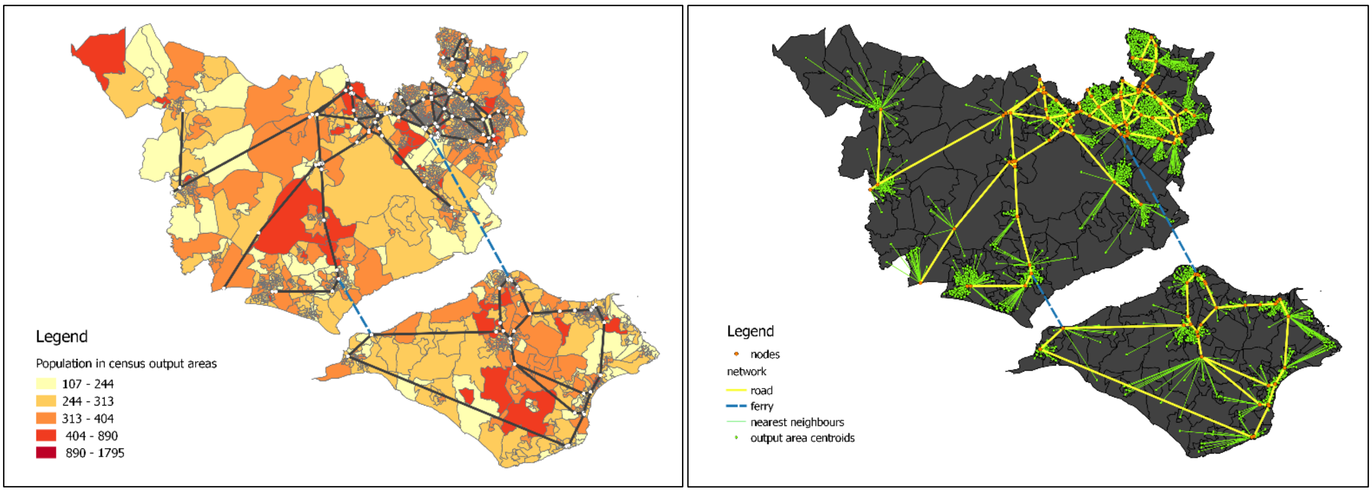

Fig. 2. (a) Population in census output areas; (b) Matching census output areas to their nearest network nodes.

3.4. Link travel time update

Link travel times are updated after the network assignment using the following formula (U.S. Bureau of Public Roads, 1964):

$$T_c = T_0\left[1 + \alpha\left(\frac{V}{C}\right)^{\beta}\right] \tag{3}$$

Where:

- T_c is a congested travel time on a link,
- T_o is a free-flow travel time on a link,
- V is hourly volume [PCU/lane/hour],
- C is average maximum road capacity [PCU/lane/hour],
- α, β are parameters (e.g. $\alpha = 0.15$, $\beta = 4$ or 5.55).

The following assumptions are made:

- Motorways: 3 lanes in each direction, maximum capacity of 2330 (from WebTAG Unit 3.9.5, DfT 2012), $\beta = 5.55$,
- A-roads: 1 lane in each direction (single carriageway), maximum capacity of 1380 (from WebTAG), $\beta = 4$,
- Passenger car unit (PCU) equivalents: 1 car = 1 PCU, 1 van = 1 PCU, 1 artic = 2 PCU, 1 rigid = 2 PCU,
- Peak-hour volume is 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 (Department for Transport, 2010b).

3.5. Skim matrix (time and cost) update

Skim matrices represent inter-zonal and intra-zonal travel times and travel costs (see Fig. 4). Travel times are computed (or updated) after the network assignment, as an average (congested) travel time across all the paths generated between an origin and a destination zone. Analogously, travel costs are calculated as average fuel cost across all the paths between an origin and a destination zone. These costs are computed assuming a fixed vehicle split over engine types (petrol, diesel, LPG, hydrogen, hybrid, electric) which is given as an input, 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). Once skim matrices are updated, the new values can be used in the last two terms of equation (2) to estimate the changes in traffic flows due to changes in inter-zonal and intra-zonal travel times and costs. Although it would be possible to iterate between flow allocation (network assignment) and flow estimation (demand prediction) until the values converge, in order to limit model run times it is proposed that only a small, fixed number of iterations is made.

3.6. Model Outputs

The road traffic model in the current Fast-Track implementation 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.
- Predicted fuel and electricity consumptions.

Fig. 4. Skim matrices are computed to obtain inter-zonal and intra-zonal travel times and costs.

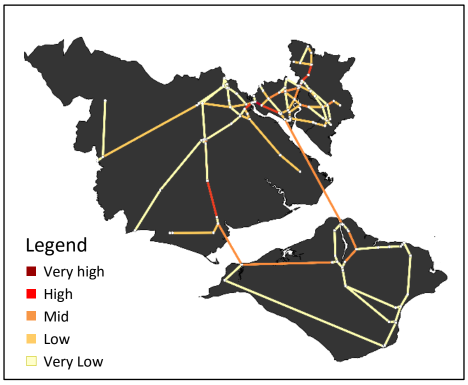

Fig. 5. Peak-hour capacity utilisation of major road links.

3.7. Policy Interventions

In the Fast-Track case study, two policy interventions have been considered and implemented:

- *Road expansion* – this intervention increases the capacity of existing road links by building new lanes. Fig. 5 shows capacity utilisation of the major road network, with red links suggesting the "pinch points" with highest levels of peak hour congestion. One such candidate for road expansion is the busiest road connecting New Forest and Southampton (see Fig. 6b). The effects of this intervention are two-fold: Initially, new lanes will decrease capacity utilisation and link travel times (see Equation 3). However, because decreased link travel times will also decrease inter-zonal travel times between New Forest and Southampton, Equation 2 will predict higher flows between these two zones, which will then increase capacity utilisation and travel times, thereby somewhat diminishing the overall efficacy of the intervention.
- *Vehicle electrification* – this intervention proposes a higher share of electric vehicles in the engine type split (see Fig 6a). The effects of the intervention are higher levels of electricity consumption compared to the base year, which are going to be passed on to the models of the energy sector, representing another cross-sectoral interdependency. This policy will also have environmental implications, which will be assessed once the environmental module is implemented.

Fig. 6. (a) Increasing the share of electric vehicles; (b) Road capacity expansion with new lanes.

4. Discussion

The first challenge encountered while developing the Fast-Track case study was lack of required data or data quality issues. For example, it was found that none of the considered road networks contained information about the number of lanes on individual road links, which is an important information for modelling road capacities accurately. While AADF road network only distinguishes between A roads and motorways, the Ordnance Survey OpenRoads network contains information whether a road is a single or a dual carriageway. Although this does give some indication of road capacities, it is still not providing precise information on the number of lanes. The AADF road network was also found to contain many topological errors such as gaps in the network that needed to be corrected for routing purposes. Finally, to obtain a fully connected road network, it will be necessary to augment the major road network with ferry lines that link mainland road networks with road networks on islands.

The second major challenge is related to model's scalability and simulation run times. This challenge is expected to become more prominent once the highway demand model developed for the Fast-Track case study is scaled to the full national road network. It is important to confine simulation run times because the MISTRAL transport model will need to run within a system-of-system model and interact with other sector models. Feasible run times of the full-scale transport model will also be necessary for model validation, calibration, uncertainty analysis, and for exploring a large number of combinations of possible future scenarios and policy interventions.

5. Conclusions

This paper presents issues, trade-offs and challenges encountered while developing a UK national transport model as part of a large interdisciplinary project, ITRC MISTRAL. The requirements and plans for the national model are presented, including the progress made so far, during the development of the Fast-Track case study (highway demand model for passenger and freight vehicles). In future work, the presented highway demand model will be refined with more realistic behavioural models and then scaled up to the full network of UK's major roads. The model will also be calibrated using the count data from the DfT's AADF project. New demand and capacity models will be developed for rail, sea and air traffic; global connectivity points will be defined; cross-sectoral dependencies implemented; and environmental emissions assessed. Finally, the model will be integrated with risk and resilience models developed within the ITRC consortium.

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