Designing a Road Traffic Model for the Cross-sectoral Analysis of Future National Infrastructure

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ITRC (Infrastructure Transitions Research Consortium):

- Interdependent infrastructure systems (transport, energy, water, waste, digital communications).
- Used by the UK’s NIC to inform its National Infrastructure Assessment.
Aspirations for MISTRAL (NISMOD v2)

- Integration of **capacity, demand** and **risk** modelling frameworks.
- System model with packages of **policy interventions**:
  - New road development.
  - New bus/rail services (e.g. HS2).
  - New technology/modes (e.g. autonomous vehicles).
  - Electrification of vehicles.
  - Congestion charging.
- **Global connectivity**: integration with international demand/supply nodes at model boundaries.
- **Risk and resilience**: identification of most vulnerable points on networks.
Fast-track Case Study (Highway Demand Model)

- Transport model predicts highway demand (OD matrix):
  - For passenger and freight vehicles.
  - Elasticity-based simulation.
  - Network assignment to major road network.
  - Implemented in Java (GeoTools).

- Fast-track case study:
  - Four local authority districts (LADs).
  - Three interventions:
    • Road expansion
    • Road development
    • Vehicle electrification
  - Cross-sectoral interdependencies:
    • Input: electricity price (per kWh).
    • Output: total electricity consumption.
Passenger demand (passenger vehicle flows) are predicted using the following formula:

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

Where:

- \( F_{ijy} \) is the flow between origin zone \( i \) and destination zone \( j \) in year \( y \).
- \( P_{iy} \) is the population in zone \( i \) in year \( y \).
- \( I_{iy} \) is the GVA per head in zone \( i \) in year \( y \).
- \( T_{ijy} \) is average travel time between zone \( i \) and zone \( j \).
- \( C_{ijy} \) is average travel cost between zone \( i \) and zone \( j \).
- Elasticity parameters are taken from previous studies.

\[ \eta_P = 1.0 \]
\[ \eta_I = 0.63 \]
\[ \eta_T = -0.41 \]
\[ \eta_C = -0.215 \]
Freight Vehicle Demand Model

- **Freight demand** (freight vehicle flows) are predicted using the following formula:

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

- Freight model uses different elasticity values and different travel time/cost matrices.
- Three types or freight vehicles: **artics**, **rigids** and **vans**.
- Freight zones can be: **LADs**, major **distribution centres**, **airports** and **seaports**.
- Adopted from the DfT’s *Base-Year Freight Matrices* study (2006).
• **Passenger vehicle demand:**

<table>
<thead>
<tr>
<th>ORIGIN LAD</th>
<th>DESTINATION LAD</th>
<th>PRODUCTIONS</th>
<th>ATTRACTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 1 1 1</td>
<td>1 1 1 1</td>
<td>400</td>
<td>260 400 500 800</td>
</tr>
<tr>
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<td>460</td>
<td>260 400 500 802</td>
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</tr>
<tr>
<td>1 1 1 1</td>
<td>1 1 1 1</td>
<td>700</td>
<td>260 400 500 800</td>
</tr>
</tbody>
</table>

- **Scaling to productions**
- **Scaling to attractions**
- **Scaling to NTS OTLD**

• **Alternative approach:** OD matrix estimation with network assignment and AADF traffic counts.

• **Freight vehicle demand:**
  - **DfT’s BYFM study (2006) -> scaling to 2015.**
  - **Three matrices (artics, rigids, vans).**
  - **Point ‘zones’: airports, seaports and major distribution centres have been mapped to their nearest node networks.**
• Origin and destination zones (LADs) are relatively large compared to the road network.

• Finer census output areas with their population size are used for the node choice.
• Population weighted centroids are assigned to the nearest neighbour nodes.

• Nodes are then ranked based on the gravitating population.
Model Flow (Network Assignment)

- For each OD (LAD) pair with a non-zero flow
  - For each trip:

  ![Diagram of model flow](image)

  - Origin node choice
  - Vehicle engine choice
  - Route choice
  - Destination node choice
  - Time of day choice

![Engine Type Fractions](image)

- Engine Type Fractions:
  - PETROL = 40%
  - HYDROGEN = 2%
  - DIESEL = 30%
  - ELECTRICITY = 25%
  - LPG = 10%

Daily trip distribution from NTS
Network Assignment (Routing)
• AADF UK major road network (A roads and motorways).
• OD flow is assigned to the least-cost path between origin and destination node.
• Fastest path (based on congested link travel times, using a heuristic search algorithm A*).
• Disadvantages:
  • All drivers choose the same optimal path.
  • Routing algorithm is costly.
• Alternative implementation: route-choice model and off-line route set generation.
Network Assignment v2 (Route Set Generation)

- **Algorithms** (e.g. k-shortest path, link elimination, random perturbation etc.)
- **Random link elimination:**
  1. Find the fastest path (A*).
  2. Eliminate a random link within that path.
  3. Find the next fastest path.
  4. If new, add to the route set.
  5. Repeat from 2 until limit reached.
- **Limit:** 10 RLE attempts, max. 5 routes per route set.
• **Route-choice model**: path-size logit

• Utility of a route is a function of:
  • Time (link travel times + intersection delay)
  • Distance (link lengths)
  • Cost (fuel cost + congestion charge)
  • Number of intersections

\[ V_{in} = \beta_1 \text{Time} + \beta_2 \text{Distance} + \beta_3 \text{Cost} + \beta_4 \text{NoInt} \]

• Variables depend on time of day and vehicle fuel efficiency.

• Path size (PS) is a correction term for overlapping alternatives.

• The probability of driver \( n \) choosing path \( i \):

\[
P(i|C_n) = \frac{e^{V_{in} + \ln PS_{in}}}{\sum_{j\in C_n} e^{V_{jn} + \ln PS_{jn}}}
\]
• **Link travel times** (for each hour of the day) are updated as (BPR):

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

- \( T_c \) is a congested travel time on a link,
- \( T_0 \) is a free-flow travel time on a link,
- \( V \) is hourly volume [PCU/ lane/ hour],
- \( C \) is max. road capacity [PCU/ lane/ hour],
- \( \alpha, \beta \) are parameters.

• **Alternative specification using fundamental diagrams of traffic flow** (FORGE, DfT).
Skim Matrices Update

- Contain inter- and intra-zonal travel times and travel costs.
- Calculated after network assignment as average travel time/cost across all the chosen routes for all the trips.
- Feeds back into the elasticity-based simulation:

\[
\left( \frac{T_{ijy}}{T_{ijy-1}} \right)^{\eta_T} \left( \frac{C_{ijy}}{C_{ijy-1}} \right)^{\eta_C}
\]
Model Flow (Demand Prediction)

Network assignment (base year)

Policy interventions (predicted year)

Demand prediction 1 (population and GVA)

Demand prediction 2 (time and cost)

Network assignment (predicted year)

OD matrix

T & C

KPIs

Road expansion

New road development

Vehicle electrification

Vehicle automation

Congestion charging

\[ F_{ijy} = F_{ijy-1} \left( \frac{P_{ij}}{P_{ij-1}} \right) \left( \frac{I_{ij}}{I_{ij-1}} \right) \left( \frac{P_{ij}}{P_{ij-1}} \right) \left( \frac{T_{ij}}{T_{ij-1}} \right) \left( \frac{C_{ij}}{C_{ij-1}} \right) \]

\[ F_{ijy} = F_{ijy-1} \left( \frac{P_{ij}}{P_{ij-1}} \right)^{\eta_p} \left( \frac{I_{ij}}{I_{ij-1}} \right)^{\eta_l} \left( \frac{P_{ij}}{P_{ij-1}} \right)^{\eta_p} \left( \frac{T_{ij}}{T_{ij-1}} \right)^{\eta_T} \left( \frac{C_{ij}}{C_{ij-1}} \right)^{\eta_C} \]
• After the network assignment of passenger and freight vehicle flows, the capacity utilisation of the road network can be assessed.

• Capacity utilisation = actual flow / max. flow

• Capacity “pinch points” can be identified – candidates for policy interventions.
• Road expansion  
  = building new lanes.
• Road development  
  = building new links.
• Expected impact:  
  – Lower capacity utilisation and decreased travel times.
  – Somewhat increased demand due to lower travel times (see the elasticity-based model).
Predicted road capacity utilisation after policy interventions:

- **(a) No intervention**
  - Bigger reduction in capacity utilisation
  - Localised effect

- **(b) Road expansion**
  - Smaller reduction in capacity utilisation
  - Spread out effect

- **(c) Road development**
• Congestion charging policy:
  – Road links on which the policy applies.
  – Pricing structure table
    \[[\text{Vehicle Type} \times \text{Time of Day (hours)}]\].

• Examples:

Itchen Bridge toll:

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>0 – 7</th>
<th>7 – 11</th>
<th>11 – 16</th>
<th>16 – 20</th>
<th>20 – 24</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAR</td>
<td>£0.50</td>
<td>£0.60</td>
<td>£0.50</td>
<td>£0.60</td>
<td>£0.50</td>
</tr>
<tr>
<td>VAN</td>
<td>£1.20</td>
<td>£1.20</td>
<td>£1.20</td>
<td>£1.20</td>
<td>£1.20</td>
</tr>
<tr>
<td>RIGID</td>
<td>£25.00</td>
<td>£25.00</td>
<td>£25.00</td>
<td>£25.00</td>
<td>£25.00</td>
</tr>
<tr>
<td>ARTIC</td>
<td>£25.00</td>
<td>£25.00</td>
<td>£25.00</td>
<td>£25.00</td>
<td>£25.00</td>
</tr>
</tbody>
</table>

London congestion charge zone:

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>0 – 7</th>
<th>7 – 18</th>
<th>18 – 24</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAR</td>
<td>£0.00</td>
<td>£11.50</td>
<td>£0.00</td>
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<td>£0.00</td>
<td>£11.50</td>
<td>£0.00</td>
</tr>
</tbody>
</table>
(a) Fuel type market shares
(b) Predicted car fuel consumptions

- Increased total electricity consumption $\rightarrow$ energy demand model.
- Reduced environmental impact.
Cross-sectoral Interdependencies

- TR – transport
- E – energy
- DC – digital communications
- SW – solid waste
- W – water

**Interdependencies** between transport and the energy sector:
- Energy supply → electricity unit price (kWh) → Transport
- Transport → total electricity consumption → Energy demand

**SMIF** (Simulation Integration Modelling Framework).
• **Major road** network for Great Britain (A roads and motorways).
• Adding **ferry lines**.
• **OD matrix estimation** (TEMPRO trip end data, trip length distr., AADF count data).
• **Calibration** with traffic counts.
• **Code optimization**.
• **Offline route set generation**.
• IRIDIS4 compute cluster of the University of Southampton.

• **Limit**: inter-zonal trips consider only top N nodes.

• **Passenger** vehicle OD matrix: 13,450,717 routes for 2,939,471 node pairs.

• **Freight** vehicle OD matrix: 12,183,615 routes for 2,604,317 node pairs.

• **Challenge**: new road development intervention.
Road Disruption

- Road disruption (e.g. due to flooding) is inputted as a list of blocked road links.
- Before network assignment:
  1. Blocked road links are removed from the road network (graph).
  2. All routes that have at least one link blocked are removed from the route set.
- Removed routes are remembered so that they can be restored.
Other Major Tasks

- National rail model.
- Airport and seaport model.
- Global interconnectivity.
- Cross-sectoral interdependencies. (T + E + DC + SW + WS)
- Integration with risk & resilience models.
- Environmental impacts.
- Validation and calibration.
Challenges

• Data (lack of, quality)
  — AADF road network (topological errors, no lane data).
  — OD matrices (no data or outdated).
  — England/Wales/Scotland (no workplace zone data for Scotland).
  — AADF count data (no accuracy).

• Optimising simulation run-times and memory use
  — Scope (multi-scale: local, national, global).
  — Policy interventions (flexible, spatially and temporally disaggregated model).
  — Cross-sectoral analysis (running together with other sectoral models).
  — May require supercomputing facilities.
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Further Information

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